Self-compacting recycled concrete: basic mechanical properties, rheology, robustness and thixotropy

Iris González Taboada

Doctoral Thesis

November 2016

Supervisor: Belén González Fonteboa

Departamento de Tecnoloxía da Construción

Programa de Doutoramento en Enxeñaría Civil[1]

E.T.S. Enxeñeiros de Camiños, Canais e Portos

UNIVERSIDADE DA CORUÑA

[1] Programa regulado polo RD 1393/2007: Programa de doutoramento de Enxeñaría Civil

Dña. **Belén González Fonteboa**, Profesora Titular de Universidad en el área de Ingeniería de la Construcción de la Universidade da Coruña,

HACE CONSTAR QUE:

La memoria "**Self-compacting recycled concrete: basic mechanical properties, rheology, robustness and thixotropy**" ha sido realizada por Dña. **Iris González Taboada**, bajo mi dirección, en el Departamento de Tecnología de la Construcción de la Universidade da Coruña, y constituye la Tesis que presenta para optar al Grado de Doctor en Ingeniería Civil de la Universidade da Coruña con Mención Internacional.

A Coruña, 22 de noviembre de 2016

Fdo: Iris González Taboada

Fdo: Dra. Belén González Fonteboa

“El que quiere escalar la montaña no debe dejarse impresionar por su altura”

Laurent Gounelle

A mis padres

ACKNOWLEDGEMENTS

At this moment, I am going to conclude this “journey” that I began four years ago. In the following lines, I would like to express my deepest appreciation to all those who supported me and gave me the chance to complete this dissertation.

First of all, I would like to express my sincere gratitude to my supervisor Belén for the continuous support and unwavering guidance throughout the course of this work. She gave me the opportunity to participate in this innovative research project and provided the space to develop my own ideas and grow both personally and professionally. In addition, I am deeply indebted to Prof. Fernando Martínez-Abella. Belén and Fernando, I cannot say thank you enough for supporting me throughout my study. I have learned a lot from you. Without your guidance and persistent help, this dissertation would not have been possible.

My sincere thanks also go to Dr. Nicolas Roussel. I am deeply grateful to him for his assistance and the valuable discussions that we had during my research stay at the IFSTTAR.

I got the chance to know many nice people in “Grupo de Construcción – gCons” of University of A Coruña. They were kind to me and provided their help when necessary. I enjoyed the experience of working with them. I will never forget them and I want to tell them “Thank you very much!”. I would like to show special gratitude to María (“a miña IP de laboratorio”) and Sindy. I want to thank them for their assistance during my research work and for their continuous and solid friendship.

I am especially and deeply thankful to Naya, Guille and Iván. Thanks a lot for your enormous patience and continuous encouragement. Without you, I would have never reached this moment. Thank you from the bottom of my heart!

And finally, my most special acknowledgement goes to my parents, for their love, support and encouragement each day of my life. All I have achieved is thanks to them and I would like to dedicate this dissertation to them.

I tried to carefully plan this “journey” from the beginning. However, each day turned out to be an unexpected challenge. Now, I notice that I will only remember the good and positive moments. I know that any work can always be improved. Perfection does not exist. *“La dernière chose qu'on trouve en laissant un ouvrage est de savoir celle qu'il faut mettre la première”* (Blaise Pascal). I will never forget this exciting “journey”. *“One’s mind, once stretched by a new idea, never regains its original dimensions”* (Oliver Wendell Holmes).

ABSTRACT

Self-compacting recycled concrete: basic mechanical properties, rheology, robustness and thixotropy

This work is focused on the study of hardened and fresh behaviour of self-compacting recycled concrete (SCRC) with different replacement percentages of recycled concrete coarse aggregate (0%, 20%, 50% and 100%).

Regarding hardened behaviour (compressive strength, modulus of elasticity and splitting tensile strength), it has been analysed how the incorporation of recycled coarse aggregate affects self-compacting concrete (SCC). To do so, a database was created with published results regarding vibrated recycled concrete. Different correction coefficients were adjusted to adapt code expressions to this type of concrete. Also, specific prediction expressions for vibrated recycled concretes were adjusted as an alternative to code formulations. Lastly, it has been concluded that both the correction coefficients and the specific expressions can be used with the same accuracy in SCRC as in vibrated recycled concrete.

Regarding fresh behaviour, the relationships between rheological and empirical parameters were analysed concluding that they show the same trend in SCRC as in SCC. In this context, the research has also studied the specificity of SCRC rheology and its influence on the fresh behaviour over time. The achieved conclusions lead to state that this specificity lies in the extra water added to compensate the recycled aggregate absorption and in the intrinsic characteristics of this aggregate.

Moreover, the SCRC robustness has been analysed through sensitivity parameters and a statistical approach, defining which factors affect it to a greater extent and which tests provide more sensitivity when this property is studied. Finally, SCRC thixotropy has been evaluated measuring also its influence on interlayer bond strength.

RESUMEN

Hormigón autocompactante reciclado: propiedades mecánicas básicas, reología, robustez y tixotropía

Este trabajo se centra en el estudio del comportamiento en estado fresco y endurecido del hormigón autocompactante reciclado (HACR) con diferentes porcentajes de sustitución de árido grueso reciclado de hormigón (0%, 20%, 50% y 100%).

En relación con el comportamiento en estado endurecido (resistencia a compresión, módulo de elasticidad y resistencia a tracción), se ha analizado cómo afecta al hormigón autocompactante (HAC) la incorporación de árido grueso reciclado. Para realizar este análisis, se ha creado una base de datos con resultados publicados sobre hormigón vibrado reciclado y se han ajustado diferentes coeficientes de corrección para adaptar las expresiones normativas a este tipo de hormigón. Asimismo, se han ajustado expresiones predictivas específicas para el hormigón vibrado reciclado como alternativa a las formulaciones de las normativas. Finalmente, se ha concluido que tanto los coeficientes de corrección como las expresiones específicas pueden utilizarse en el HACR con la misma precisión que en el hormigón vibrado reciclado.

Por lo que respecta al comportamiento en estado fresco, se han analizado las relaciones entre parámetros reológicos y empíricos concluyéndose que siguen la misma tendencia en el HACR que en el HAC. En este contexto, la investigación ha estudiado también la particularidad de la reología del HACR y su influencia en el comportamiento en fresco con el transcurso del tiempo. Las conclusiones alcanzadas permiten exponer que esta particularidad radica en la cantidad de agua extra añadida para compensar la absorción del árido reciclado y en las características intrínsecas de este árido.

Además, se ha analizado la robustez del HACR a través de parámetros de sensibilidad y de una aproximación estadística, definiéndose qué factores afectan en mayor medida y qué ensayos proporcionan más sensibilidad cuando se estudia esta propiedad. Por último, se ha evaluado la tixotropía del HACR midiéndose también su influencia en la adherencia entre capas.

RESUMO

Formigón autocompactante reciclado: propiedades mecánicas básicas, reoloxía, robustez e tixotropía

Este traballo céntrase no estudo do comportamento en estado fresco e endurecido do formigón autocompactante (FACR) con diferentes porcentaxes de substitución de árido groso reciclado de formigón (0%, 20%, 50% y 100%).

No referente ao comportamento no estado endurecido (resistencia a compresión, módulo de elasticidade e resistencia a tracción), analizouse como afecta ao formigón autocompactante (FAC) a incorporación de árido groso reciclado. Para levar a cabo esta análise, creouse unha base de datos con resultados publicados sobre o formigón vibrado reciclado e axustáronse diferentes coeficientes correctores para adaptar as expresións normativas a este tipo de formigón. Así mesmo, axustáronse expresións preditivas específicas para o formigón vibrado reciclado como unha alternativas ás formulacións das normativas. Finalmente, concluíuse que tanto os coeficientes correctores como as expresión específicas se poden empregar no FACR coa mesma precisión que no formigón vibrado reciclado.

Polo que respecta ao comportamento no estado fresco, analizáronse as relacións entre parámetros reolóxicos e empíricos concluíndose que seguen a mesma tendencia no FACR que no FAC. Neste contexto, a investigación estudou tamén a particularidade da reoloxía do FACR e a súa influencia no comportamento en fresco co transcurso do tempo. As conclusións alcanzadas permiten expoñer que esta particularidade radica na cantidade de auga extra engadida para compensar a absorción do árido reciclado e nas características intrínsecas deste árido.

Ademais, analizouse a robustez do FACR a través de parámetros de sensibilidade e dunha aproximación estatística, definíndose que factores afectan en maior medida e que ensaios proporcionan máis sensibilidade cando se estuda esta propiedade. Por último, avaliouse a tixotropía do FACR medíndose tamén a súa influencia na adherencia entre capas.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER I
Introduction

1 INTRODUCTION

In recent decades, the economic politics of most governments has led to a production pattern based on the continuous supply of material resources from the natural environment, which eventually ends up as waste. This problem has been notoriously prevalent in the construction sector which has contributed to environmental degradation, producing a high amount of construction and demolition debris (C&D debris) and consuming large volumes of natural resources.

In order to promote sustainable economic growth and ensure sustainable consumption, the United Nations has recently established a new universal set of goals, targets and indicators that member states will be expected to use to outline their political policies over the next 15 years. In accordance, every country will be expected to work towards achieving the 17 main goals established by 2030. These objectives include, but are not limited to, the suitable management of seas, oceans and forests in order to conserve marine and terrestrial resources, combat desertification and reverse land degradation [SDGs15] (Figure I-1).

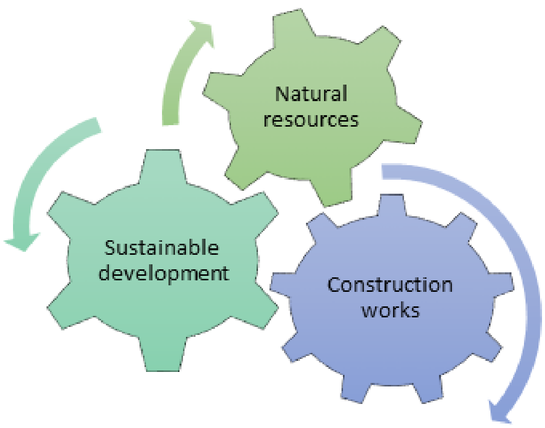


Figure I-1. The key idea in the construction sector

In this sense, recycled concrete (RC) has been widely recognised as a means to minimize environmental impact and hence, in recent years many researchers have carried out work on its use [EVAN07, CORI09, DAPE11, XIAO13a, GONZ14, CARR15, BRIT16]. Most of them conclude that recycled aggregate from concrete demolition waste provides good enough features for its use in structural concrete. Indeed, with a recycled aggregate content up to 20-30% the degradation of its mechanical properties is unappreciable [XIAO12]. However, the use of high replacement percentages reduces the mechanical strengths of concrete, especially when low quality recycled aggregates are used [BUTL13, ETXE07b, AJDU02].

Many developments were carried out in the field of structural engineering in order to correlate the required properties of concrete to be cast with the structure to be built. This last step has been missing for years in the fresh concrete properties field. Only recently, researchers have started to work on casting prediction tools [KOVL11]. This new research area has appeared at the same time as self-compacting concrete (SCC). “More fluid” is one of the big trends of the last twenty years in the field of modern concretes [ROUS06d]. SCC can flow through and fill the gaps of reinforcements, corners of moulds and voids of rock blocks without any need for vibration and compaction during the placing process, which improves the overall efficiency of concrete construction projects. The use of SCC leads to durable and reliable concrete structures [OKAM03, ZHAN16] and this extremely fluid concrete is expected to be the answer to casting problems. On the other hand, producing a robust, low viscous and low yield value SCC can be really difficult. It is almost an art [WALL06].

As an innovative material, self-compacting recycled concrete (SCRC) links the characteristics of both recycled concrete and self-compacting concrete, satisfying the new construction requirements. Although the use of recycled aggregate is an important indicator of a country’s potential growth, its use in SCC is a relatively new research area and limited studies have been carried out. Also a robust SCRC is almost an art since an only suitable type of SCRC for all applications does not exist, as happens with conventional SCC. Therefore, the study of SCRC in this dissertation will try to obtain significant results both from the aspects of science and practical use.

2 RESEARCH OBJECTIVES

The main goal of this study is to apply the principles of rheology to self-compacting recycled concrete in order to deeply understand its fresh-state behaviour and also to analyse its basic mechanical properties. In this work, recycled aggregate will refer to recycled concrete coarse aggregate. Different SCRC mixes are designed replacing the natural coarse aggregate by the recycled one and also different mixing methods have been used.

According to the literature, self-compacting concrete is expected to present properties in hardened-state similar to those of its equivalent vibrated concrete. Therefore, the first general objective of this work is to prove that it is possible to predict the SCRC properties (compressive strength modulus of elasticity, and splitting tensile strength) using proposed expressions adjusted with vibrated recycled concrete.

On the other hand, in fresh-state, SCRC is expected to show a greater influence of RC and SCC singularities (the particular properties of recycled aggregate and a particular fresh behaviour, respectively). Therefore, this work also aims to investigate how SCRC can be produced with the right workability characteristics (filling ability, passing ability and segregation resistance), rheology and robustness, and to study its thixotropic behaviour.

In this sense, the other general objective is to determine the effect of the incorporation of recycled concrete coarse aggregate on the fresh-state properties of self-compacting concrete. The study focuses on the time-dependent rheological behaviour of SCRC (including the evolution of its workability characteristics over time), on the evaluation of its robustness and on the analysis of its thixotropy (evaluating, moreover, its influence on the interlayer bond strength).

This research has been funded by two projects entitled: (a) “Industrial Investigation about Concrete for a Sustainable Market (InHorMeS)” funded by the Innovation Galician Agency; (b) “Robust self-compacting recycled concretes: rheology in fresh state and mechanical properties (Ref: BIA2014-58063-R)” funded by MINECO. Moreover, this work was also possible by the financial support of a pre-doctoral grant of Xunta de Galicia (Spain), also including the INDITEX-UDC 2015 grant for international pre-doctoral stays.

3 OUTLINE OF THIS DISSERTATION

This dissertation is organised into nine chapters, followed by the bibliographical references. Each of them is further divided into sections and sub-sections to clearly present all results and discussion obtained with this work.

A brief overview of the contents of each chapter is presented in the following items.

Chapter I deals with the introduction, the research objectives and the outline of the dissertation.

Chapter II reviews the main findings from the literature about recycled concrete aggregate, recycled concrete, self-compacting concrete and self-compacting recycled concrete. The former is studied using database analysis, and various aspects of RC, SCC and SCRC technologies are presented. Firstly, there is an emphasis on general requirements in terms of materials, mix proportions and mixing procedure. Next, the fresh and basic hardened properties of the three types of concrete are explained.

Chapter III deeply describes the experimental program carried out in this work. Firstly, it is described how the SCRC mixes were designed along with their constituent materials and mix proportions. Secondly, the mixing procedures are detailed and lastly, the testing methods and protocols adopted to evaluate the hardened properties and quantify the rheology, robustness and thixotropy of self-compacting recycled concrete are explained.

Chapter IV analyses the hardened-state behaviour of recycled concrete (i.e. vibrated recycled concrete) and self-compacting recycled concrete. Different prediction expressions for compressive strength, modulus of elasticity and splitting tensile strength are adjusted using a database created with published results regarding vibrated recycled concrete. The analysis is focused on determining if the incorporation of recycled concrete coarse aggregate affects SCC to a similar extent as it affects vibrated concrete and if the obtained expressions can be used with the same accuracy in vibrated recycled concrete as in SCRC.

Chapter V shows the results of fresh-state behaviour of all studied SCRCs. Results obtained with rheometer and with empirical tests are presented and also their evolution over time.

In this context, chapter VI is focused on the analysis of fresh-state behaviour regarding workability and rheology of SCRC. It discusses the relationships between empirical parameters and between empirical and rheological ones analysing if they show the same tendency in conventional and recycled self-compacting concretes. On the other hand, it analyses the specificity of SCRC rheology and finally, it studies how the rheology of SCRC evolves over time.

Chapter VII is focused on the analysis of fresh-state behaviour regarding robustness of SCRC. Modifications in the water (±W = ±3%), superplasticiser (±S = ±5%) and cement (±C = ±3%) are imposed to observe the capacity of SCRC to keep its properties when quantities of these materials are changed. The analysis of SCRC robustness is made through the calculation of sensitivity parameters and then a statistical approach is carried out to determine which tests provide more sensitivity when SCRC robustness is evaluated.

Chapter VIII analyses the thixotropy of SCRC using three testing methods: structural breakdown curves at various rotational speeds, hysteresis loop flow curves and yield stress at rest. Finally, the influence of thixotropy on the interlayer bond strength is studied using flexural tests and water permeability tests.

Chapter IX presents the conclusions and some areas are also recommended for future research.

Chapter X reports, firstly, a sequence of alphabetical order for the references cited in the text of all chapters. Then, the references used to create the database of recycled concrete aggregate (presented in Chapter II) are listed. Finally, the references used to create the database of recycled concrete (developed in Chapter IV) are shown.

Some of the works described in this dissertation have contributed to the publication of some research papers and others are in the process of publication:

- González-Taboada, Iris, González-Fonteboa, Belén, Roussel, Nicolas, Martínez-Abella, Fernando. Rheology and robustness of self-compacting recycled concrete. *Cement and Concrete Composites*, under review.
- González-Taboada, Iris, González-Fonteboa, Belén, Pérez-Ordóñez, Juan Luis, Eiras-López, Javier. Prediction of self-compacting recycled concrete mechanical properties using vibrated recycled concrete experience. *Construction and Building Materials*, under review.
- González-Taboada, Iris, González-Fonteboa, Belén, Martínez-Abella, Fernando, Pérez-Ordóñez, Juan Luis. Prediction of the mechanical properties of structural recycled concrete using multivariable regression and genetic programming. *Construction and Building Materials*, vol. 106, pp. 480-499, 2016.
- González-Taboada, Iris, González-Fonteboa, Belén, Martínez-Abella, Fernando, Carro-López, Diego. Study of recycled concrete aggregate quality and its relationship with recycled concrete compressive strength using database analysis. *Materiales de Construcción*, vol. 66 (323), 2016.
- Seara-Paz, Sindy, González-Fonteboa, Belén, Martínez-Abella, Fernando, González-Taboada, Iris. Time-dependent behaviour of structural concrete made with recycled coarse aggregates. Creep and shrinkage. *Construction and Building Materials*, vol. 122, pp. 95-109, 2016.
- Carro-López, Diego, González-Fonteboa, B., de Brito, Jorge, Martínez-Abella, F., González-Taboada, I., Silva, Pedro. Study of the rheology of self-compacting concrete with fine recycled concrete aggregates. *Construction and Building Materials*, vol. 96, pp. 491-501, 2015.

CHAPTER II
Literature review

1 INTRODUCTION

In this chapter, firstly, recycled concrete aggregate is reviewed with a special emphasis on its properties and its influence on compressive strength of recycled concrete. In the next sections, this chapter shows a general overview of the properties of recycled concrete (RC), self-compacting concrete (SCC) and self-compacting recycled concrete (SCRC), highlighting the influence of materials used on their characteristics in fresh and hardened states. In the last section, the specific objectives of this dissertation are summarized.

2 RECYCLED CONCRETE AGGREGATE

This section studies the physical and mechanical properties of recycled concrete aggregate (recycled aggregate from concrete waste) and their influence on structural recycled concrete compressive strength. It is a study of recycled concrete aggregate quality and its relationship with recycled concrete compressive strength using database analysis.

2.1 Introduction and scope of this section

In recent decades, a social movement of environmental awareness has developed where the protection of natural resources and sustainable development play an essential role in the modern requirements of construction works [OIKO05, MEYE09, COLL15, GRIS15]. The use of recycled concrete aggregate has increased in recent years backed by extensive scientific research. A significant number of research papers have been published which has reduced the uncertainty related to its performance. Therefore, the creation of a database [references 1-152, Chapter X, section "References – Recycled concrete aggregate database"] including these published results (Figure II-1) is very useful for making general conclusions.

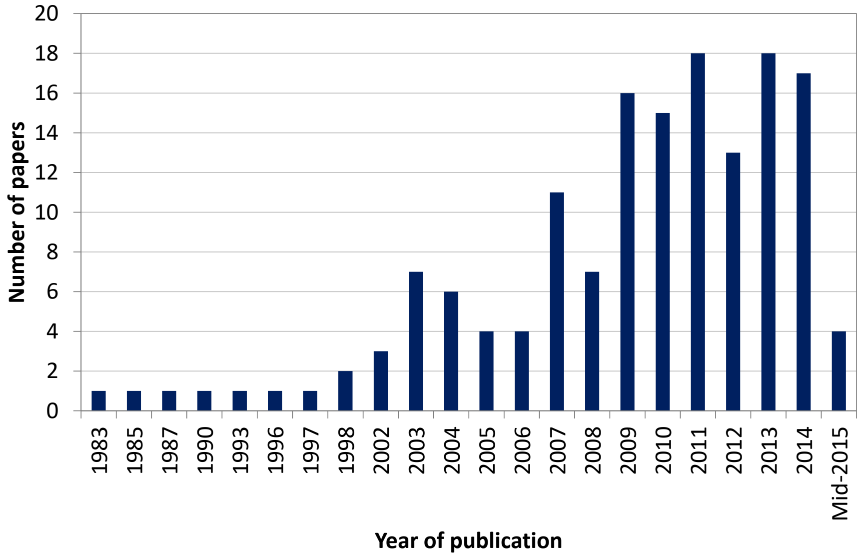


Figure II-1. Year of publication vs. Number of papers (recycled concrete aggregate database)

The objective of this database analysis is to achieve a full understanding of recycled concrete aggregates and propose a design methodology for structural recycled concrete, based on the physical-mechanical properties of recycled concrete coarse aggregates studied using the database.

The quality of recycled aggregate concrete depends on the properties of the recycled aggregates. This section deals with the study of aggregates recycled from concrete waste, which are the most suitable aggregates for creating structural recycled concrete. Apart from the natural aggregate, the other main component of this recycled aggregate is the adhered cement mortar. This material is the cause of the main differences between natural aggregates and recycled concrete aggregates [AKBA13, PAIN10a].

Undoubtedly, there is significant variation in the quality of this kind of aggregate. Firstly, it is related to the original concretes and their differences. Low grade original concrete leads to low grade adhered mortar and consequently, low grade recycled aggregates. Secondly, the recycling process is also important because it influences the amount (quantity) of attached mortar, which decreases as the stages in the crushing process increase [NAGA04]. Finally, it should be noted that there is a significant difference between the properties of recycled coarse aggregates and recycled fine aggregates which always contain a much higher proportion of adhered mortar.

Therefore, the original concrete, the recycling process and the size fraction are the three most important issues that should be controlled when producing recycled concrete aggregates.

From a practical point of view, it would be very interesting to establish patterns or relationships between the different physical-mechanical properties of recycled aggregate and also, between these properties and recycled concrete compressive strength.

To achieve this objective, a database has been developed [references 1-152, Chapter X, section "References – Recycled concrete aggregate database"]. This database has been built using 152 works that deal with recycled concrete aggregates, after studying over 250 international works related to recycled aggregates. The inclusion criterion was the fact that the characterization of the aggregates used should be shown, both for natural and recycled aggregates, and this characterization should include at least the following values: size fraction, water absorption, saturated surface dry density and, whenever possible, composition, Los Angeles coefficient, shape coefficient, fineness modulus and other types of density.

Recently, a wide range of reviews have been published by authors proposing a performance-based classification for the use of recycled aggregates in concrete construction [SILV14] and a model to predict the strength loss based on the quality and content of recycled aggregates [SILV15a]. Others have modelled the compressive strength of recycled concrete using artificial neural networks [DUAN13a], while others have presented a range for recycled concrete components using sensitivity analysis with neural networks [KIM13], although no expressions have been presented.

However, the objective of this work is not to propose a prediction methodology for recycled concrete compressive strength. There are many variables that influence recycled concrete compressive strength (grading curves, maximum size fraction, natural aggregate source, cement class, possible admixtures, etc.) which have not been taken into account. In fact, it is really difficult to take all these variables into account. Furthermore, compressive strength is usually experimentally measured and adjusted after different mixing tests. Consequently, the objective of this section is to analyse how the recycled concrete aggregate (both percentage and quality) and the mixing procedure (pre-soaking or adding extra water) influence the recycled concrete strength of different categories (high or low water to cement ratios), in order to establish suitable production or manufacturing recommendations to promote further use of recycled concrete.

2.2 Properties of recycled concrete aggregates

2.2.1 Composition

Recycled aggregates are defined as aggregates obtained from the treatment of inorganic material which has been previously used in construction [ACHE06]. The raw material is the waste material generated during the construction and demolition processes. Regarding the particular case of recycled concrete aggregate, this is obtained from the recycling process of concrete waste material.

Therefore, the recycled concrete aggregates are mainly made of natural aggregate and adhered cement mortar. However, it may incorporate impurities and contaminants, which have a negative influence on the properties of the final recycled concrete [YILD15]. These impurities can be very diverse, such as plastic, wood, gypsum, bricks, ceramics, organic material, asphalt, aluminium, etc.

The composition of the recycled aggregates depends on the type of original waste, the recycling plant production process and the size fraction obtained through the crushing process, and can differ depending on these three factors.

Aggregate from concrete demolition and debris generally presents a low quantity of impurities, however, the results for the compositions of recycled concrete aggregates obtained from literature are not significant enough to encounter any kind of relationship. Figure II-2 shows an example of the composition of these aggregates measured according to the European Standard EN 933-11 “Classification test for the constituents of coarse recycled aggregate” [EN933-11]. It can be seen that materials from concrete (mortar, aggregates and aggregates with mortar) make up over 90% of the total.

Most standards and recommendations classify recycled aggregates in terms of their composition [GONÇ10]. In the case of recycled aggregates suitable for recycled concrete, a minimum material from concrete waste of 90% is usually imposed (Brazilian, German, Rilem and Belgian standards) and also a maximum of 10% masonry material is established. In the United Kingdom, the Netherlands, Norway and Denmark, more than 95% of waste concrete is required and the masonry limit is fixed at 5% [GONÇ10, BSI02, DIN02, LNEC06, OT06, RILEM94, WBTC02]. The Spanish standard [EHE08] establishes a maximum of masonry content at 5%, of lightweight material at 1%, of asphalt at 1% and finally, the sum of other materials like glass, plastic, metals, etc. must be under 1%.

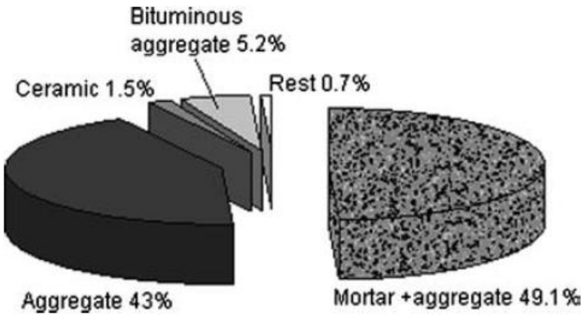


Figure II-2. Recycled concrete aggregates composition [ETXE07a]

In general, with a suitable crushing process, the recycled coarse aggregates from waste concrete can deal with these limits.

2.2.2 Adhered mortar

The main differences between recycled concrete aggregate and natural aggregate are due to the presence of adhered cement mortar [PEDR14a]. This new material makes the aggregate density lower and the water absorption and Los Angeles coefficient higher, which means lower fragmentation resistance. Consequently, the quality and quantity of adhered mortar is one of the key factors controlling the quality of recycled concrete aggregates and, indeed, the performance of recycled concrete.

It is well known that the quality and quantity of adhered mortar is influenced by the quality of the original or parent concrete, production treatment designed in production plants and size fraction of the aggregates.

The influence of the original concrete is not clear. Some researchers explain that, during the crushing process of low strength original concrete, most of the mortar gets separated from the original aggregate because the bond between mortar and aggregate is weak. As this mortar gets crushed into fine particles, it is then removed during the sieving process. Therefore, the recycled coarse aggregate obtained from this low strength original concrete presents a lower quantity of mortar. However, others explain that the quality of attached mortar in recycled aggregates is lower when obtained from low strength original concretes than when obtained from high strength ones, as the water to cement ratio of the low strength concretes is high and hence, the mortar obtained with them is more porous.

With regards to production, a number of works can be seen in the literature which propose the improvement of recycled aggregate quality by reducing the adhered mortar using special production treatments. There are different treatment options, with some authors proposing one or a combination of mechanical grinding processes (also increasing the number of crushing processes [JUAN09]), others using thermal treatments (microwave or conventional heating) [AKBA11] and, finally, others using chemical treatments (pre-soaking or cycle soaking the recycled aggregates in different acidic solvents, namely hydrochloric acid, sulphuric acid, and phosphoric acid) [TAM07]. In this regard, an investigation has been carried out that deals with the influence of different polymer treatments on recycled aggregates that has been already used in the protection of structures (grout, render, etc.) [SPAE13]. However, so far none of these treatments has been developed in the industry.

Finally, it is also clear that the crushing process reduces the size of waste material and, as the weakest phase of this material is the adhered mortar, it will be more affected by the crushing process than the original aggregates. In this regard, the fine fractions will be mainly composed of adhered mortar. Therefore, the greater the quantity of adhered mortar the finer the size fraction of aggregate.

The presence of adhered mortar implies that, while conventional concrete is a three-phase composite material (on a microscopic scale) with a mortar matrix, aggregates and one interfacial transition zone between these two zones (paste-aggregate interface), recycled concrete has two interfaces, the interface between adhered mortar and the original aggregate and the new interfacial transition zone between the new mortar and the recycled aggregate. The adhered mortar makes bonding between the recycled aggregate and the new mortar (new interface, Figure II-3) weaker, which leads to worse recycled concrete performance, affecting properties related to deformation (modulus of elasticity, drying shrinkage and creep), durability (water absorption and permeability) and, of course, mechanical behaviour (strength) [GONZ05, HANS83]. Moreover, the adhered mortar also controls the concrete's workability. As the adhered mortar increases, the water absorption also increases and the fresh mixture's workability decreases.

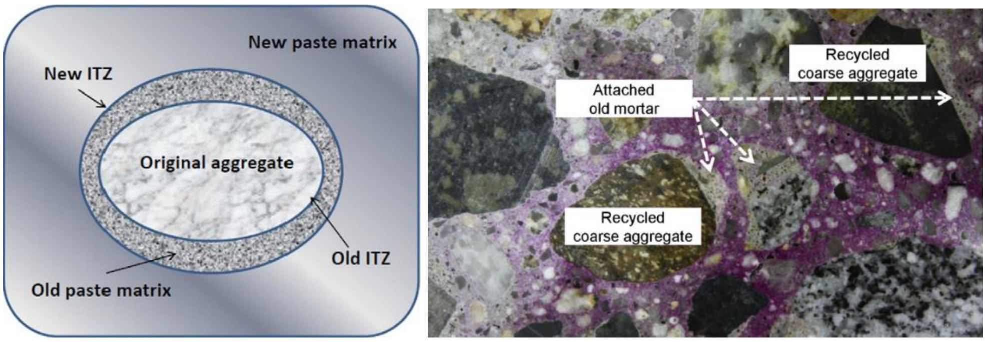


Figure II-3. Recycled aggregate interface [LI12] [SEO14]

Regarding the mortar content, the literature shows some randomness. Hansen and Narud [HANS83] reported that the mortar content varied from 30, 39 and 60 percent for 16-30 mm, 8-16 mm and 4-8 mm fractions respectively and assessed that original concrete quality hardly influences this quantity. However, according to Li [LI08], the percentage of old mortar (around 20-30%), mainly depends on the properties of the original concrete and the production process. Ravindrarajah and Tam [RAVI85] stated that, in general, recycled coarse aggregates contain an average of about 50% adhered mortar. On the other hand, Sánchez and Alaejos [JUAN09] found ranges of 23-44% for 8-16 mm fraction and of 33-55% for 4-8 mm fraction. This heterogeneity of results is probably due to the difficulty in measuring the adhered mortar quantity, the different original concretes used and, of course, the different treatments designed to manage construction and demolition waste.

2.2.3 Shape and particle size distribution

Recycled aggregate grading is directly linked to the crushing process applied to the original concrete waste [JUAN04]. Furthermore, this process is restricted by the grading curves set out by countries in their regulations [ACHE06].

If a grain size distribution analysis of natural and recycled aggregates is carried out, a different pattern of behaviour is observed for coarse and fine aggregates. The grain size distribution of recycled coarse aggregate does not differ appreciably from natural coarse aggregates, although higher content of sand is incorporated in recycled coarse aggregate than in natural one [SAFI11, SILV16]. Hence, the recycled aggregate fineness modulus undergoes small variations for the same maximum aggregate size, depending mainly on the crushing process used and the original concrete quality [LOPE08].

However, the recycled fine aggregate grading generally shows thicker size fractions than conventional fine aggregate. Debieb et al. [DEBI10] even points out that recycled sand consists mainly of gravel and a small quantity of medium-sized sand.

Seventy-one different datasets were considered in the database. The fineness modulus obtained from different authors vary in the range of 5.70 to 7.36 for maximum aggregate sizes between 10 and 25 mm, as shown on Figure II-4, with an average value of 6.55.

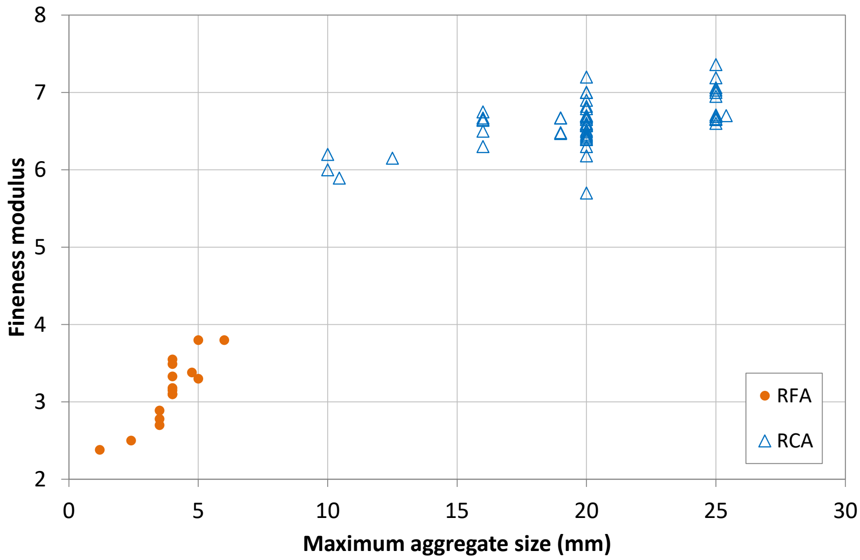


Figure II-4. Recycled concrete aggregate fineness modulus vs. Maximum aggregate size

Note: RCA (recycled coarse aggregate); RFA (recycled fine aggregate)

Due to the presence of attached mortar, the surface texture of the recycled coarse aggregates is found to be more porous and rough [BAIR93, JUAN04, YOUN13] than that of the natural aggregate.

Furthermore, it should be taken into account that recycled aggregate generates fines during its manipulation due to the production of small mortar particles. The presence of these fine particles in the recycled coarse aggregate may decrease the bond between the recycled aggregate and the new cement paste and increase the mixing water necessary to achieve fixed workability when the concrete is made [SEAR14]. The Spanish standard limits the fines content to 1% [EHE08]. The Belgian, British and German codes, the Rilem recommendation and the Hong Kong specifications establish a higher limit, which is between 2% and 5% [ACHE06, BSI02, DIN02, RILEM94, WBTC02].

In general, the particle shape of recycled aggregates is determined by the crushing equipment. Impact mills used in recycling plants produce cube-shaped aggregates because concrete tends to break into small blocks without generating slabs [MART11]. In this way, the shape index of recycled and natural coarse aggregate is similar. According to the studies checked [BARB13, JUAN04, OLIV96, ETXE07b, FONS11, GOME02, GONZ05, LOPE14, VIEI11, GONZ08, GONZ02], this index presents a range of values from 0.14 to 0.47 when recycled aggregate is analysed and from 0.19 to 0.58 for natural aggregate. In general, the limit established in the Spanish specification [EHE08] can be fulfilled without any problem.

2.2.4 Water absorption

The database has verified the usual statement that the water absorption of recycled aggregates is much higher than that of natural aggregates [references 1-152, Chapter X, section "References – Recycled concrete aggregate database"]. The main reason for this difference is the presence of cement mortar that remains attached to the recycled aggregate particles. This cement mortar has higher porosity than the aggregates and therefore, recycled aggregates absorb more water than the conventional kind.

The natural aggregate water absorption usually ranges between 0% and 4%. However, drawing an analysis from the database (two hundred and ninety-nine datasets), the water absorption values obtained for recycled aggregates ranges from 1.65% to 13.1%, with an average value of 5.32%.

Furthermore, because of the fact that the percentage of adhered mortar is higher in the sand fraction than in the coarse fraction [ZAHA03], water absorption increases as the size fraction decreases. As already noted, since the weakest phase of waste material is the adhered mortar, it will be more affected by the crushing process than the original aggregates. In this regard, the fine fractions will mainly consist of adhered mortar.

This trend is shown on Figure II-5, highlighting the important influence of the size of recycled aggregate on its water absorption capacity. In this regard, the water absorption of recycled coarse aggregate varies from 1.12 to 8.82%, with an average value of 5.06%, whereas the water absorption of recycled fine aggregate varies from 6.84% to 13.1%, with an average value of 9.89%. However, for the same maximum aggregate size some scatter can be observed, due to the fact that this property is also influenced by the original waste and the crushing processes.

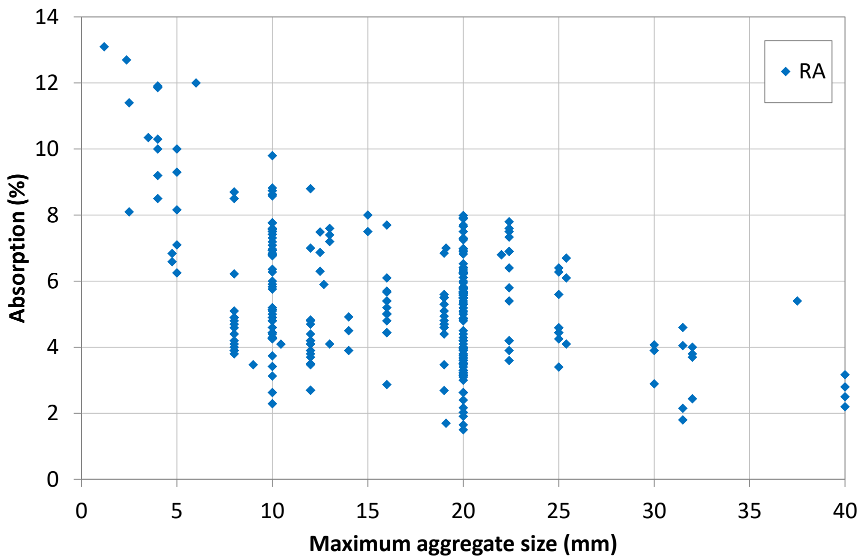


Figure II-5. Water absorption vs. Maximum aggregate size

Note: RA (recycled aggregate)

With regards to original waste, a high quantity of impurities (especially ceramic material) will increase water absorption. However, once again, the influence of the original concrete is not clear, with some researchers indicating that high grade original concrete can make water absorption lower [HANS83, NAGA04] while others [CHAK11, PADM09] state that the water absorption of recycled aggregates increases as the original concrete strength increases. This depends on whether the main effect is the quantity of adhered mortar (low strength original concrete presents lower quantity of mortar) or its quality (low strength concrete presents more porous adhered mortar).

Finally, concerning the crushing process, it is clear that a high number of crushing processes leads to lower water absorption values [ETXE07b, LOPE08], due to the fact that these crushing processes reduce the size of the cement adhered mortar which is finally eliminated during the sieving process.

Most international standards set out limits for the water absorption of recycled aggregate. The Rilem recommendations establish a maximum value of 10% for aggregate type II, an aggregate mostly from concrete rubble (ceramic content under 10%) [RILEM94]. This value is also accepted in the recommendations of Hong Kong and Norway [GONÇ10, WBTC02]. In the German standards, maximum water absorption after 10 minutes is established at 10% [ACHE06]. The Belgian specifications are very similar to the Rilem, establishing maximum water absorption at 9% for the recycled aggregate known as GBSB-II, which is the equivalent of the aforementioned aggregate type II. The Australian guide only admits a water absorption capacity of 6%. In Japan, different requirements are demanded depending on the application of the aggregates [JIS05, JIS06, JIS07]; when the highest grade of recycled aggregate (type H) is analysed, the water absorption capacity must be under 3%. The Brazilian and Portuguese specifications allow a maximum water absorption value of 7% [LNEC06, NBR05]. The Spanish standard [EHE08] establishes the limit at 7%, when only 20% of recycled coarse aggregate is going to be used and the natural coarse aggregate shows a water absorption capacity lower than 4.5%. When more than 20% of recycled coarse aggregate is going to be used, the mix of natural and recycled coarse aggregate should maintain an absorption capacity no greater than 5%.

Actually, water absorption develops over time, with the European Standard EN 1097-6 [EN1097-6] establishing that it should be measured after soaking aggregates in water for at least 24 hours. However, many authors agree with the fact that in the first 10 minutes the recycled coarse aggregates can achieve 80-90% of their water absorption capacity [AGRE11, AKBA11, RÜHL92]. For this reason water absorption at 10 minutes is a very useful value when designing, as it can be used to calculate the extra water needed to maintain workability or define the pre-soaking aggregate time.

Belin et al. [BELI14] concluded that water absorption at 24 h can be seen as the simple sum of the capillary absorption of both residual cement paste and initial natural aggregates. They propose a tentative framework for the classification of recycled concrete aggregate based on the water absorption rate and the water absorption capacity at 24 h.

On the other hand, Djerbi [DJER12] has obtained a long saturation time for recycled aggregates (>24 h). He concludes that the standard method of 24 h stipulated in European standards is not suitable for water absorption measurements of recycled aggregates. The water absorption coefficient of recycled aggregates for 24 h of soaking produces about 60% and 70% of the total water absorption obtained after 85 h and 110 h of soaking for the 12.5–20 mm fraction and 5–12.5 mm fraction respectively. He presents a hydrostatic weighing approach and concludes that this new approach allows engineers to determine the test time and that it improves the precision of water absorption measurements for aggregates.

2.2.5 Saturated surface dry density

Recycled concrete aggregate density is proved to be lower than that of natural aggregate. Surface dry density or SSD density is often used in the field of concrete.

As a general rule, it is verified that the higher the content of attached mortar and impurities, the lower the recycled coarse aggregate density [MART11]. In this regard, again, this property is influenced by the original waste, processing level and size fraction.

Adhered mortar is a porous material with a density of around 1.0–1.6 Kg/m3, which is lower than that of natural aggregate particles [TAM08]. Furthermore, the adhered mortar porosity depends on the water/cement ratio of the parent concrete. Higher strength original concrete provides denser and higher quality adhered mortar, than that obtained from lower strength concrete. However, again, the quantity of cement mortar will be higher in recycled coarse aggregate obtained from high strength concrete. Finally, the type and density of virgin aggregate also plays an important role. Some researchers indicate that it affects recycled aggregate properties more than the water to cement ratio of the original concrete [ZEGA10].

Once again, as the weakest phase of the virgin waste material is the adhered mortar, this will be affected to a greater extent by the crushing process than the original aggregate. In this regard, the adhered mortar will mainly be present in the fine fractions.

Regarding the multiple crushing of source concretes, this reduces the number of particles with cracks, microdefects or voids in the coarse fractions of aggregate. Furthermore, again, the crushing process reduces the size of the adhered cement mortar (weak and easily crushed) which is finally eliminated during the sieving process (powder) or used as recycled fine aggregate. Consequently, the recycled concrete coarse aggregate obtained at each stage of the recycling process improves in density value. Some countries have tried to develop a closed-loop recycling system to improve the coarse aggregate properties and, at the same time, handle the large amount of crushed concrete fines and powder generated during the recycling process for producing recycled cement.

Figure II-6 shows the relationship between maximum aggregate size and density values. As the aggregate size increases, the density value also increases (due to the fact that the adhered mortar content has decreased with the aggregate size). For the same size fraction, some scatter in the data from the literature (two hundred and seventy-four datasets) (Figure II-6) is observed. This is due to the different qualities of the original waste (this property is influenced by original aggregate density) and, also the number of crushing processes undergone by the concrete debris.

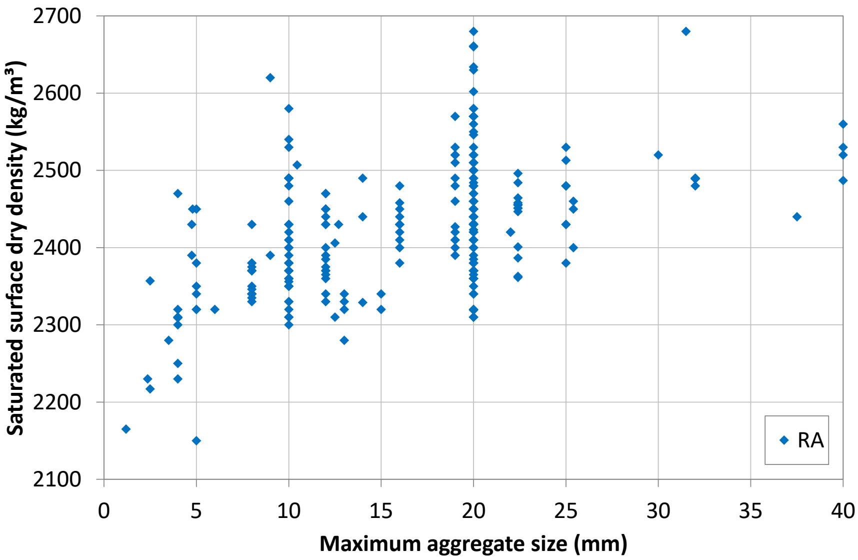


Figure II-6. Saturated surface dry density vs. Maximum aggregate size

Note: RA (recycled aggregate)

The SSD density of the recycled concrete aggregate ranges from 2150 to 2680 kg/m³. The density values of recycled coarse aggregate vary from 2280 to 2680 kg/m³, higher than that of fine aggregate. This recycled coarse aggregate presents an average value of 2397 kg/m³ for a particle size under 16 mm and 2458 kg/m³ when higher fractions are analysed. The average value of the SSD density of the recycled coarse aggregate is 2437 kg/m³. On the other hand, fine aggregate (maximum size fraction under 4 mm) shows SSD density values, generally, under 2350 kg/m³ and an average value of 2312 kg/m³.

The standards for Germany, Hong-Kong, Netherlands, Portugal, Norway and Denmark and the RILEM recommendation establish a minimum density value for recycled concrete aggregate between 2000 and 2200 kg/m³. The Rilem recommendation considers that the percentage of material with an SSD density value under 2200 kg/m³ must be under 10% [ACHE06, GONÇ10, DIN02, RILEM94, WBTC02].

All authors point out that as water absorption increases, SSD density decreases. This trend can be observed on Figure II-7 (two hundred and forty-seven datasets) which represents the relationship between SSD density and the water absorption capacity. The expression which links both values changes as a function of aggregate size.

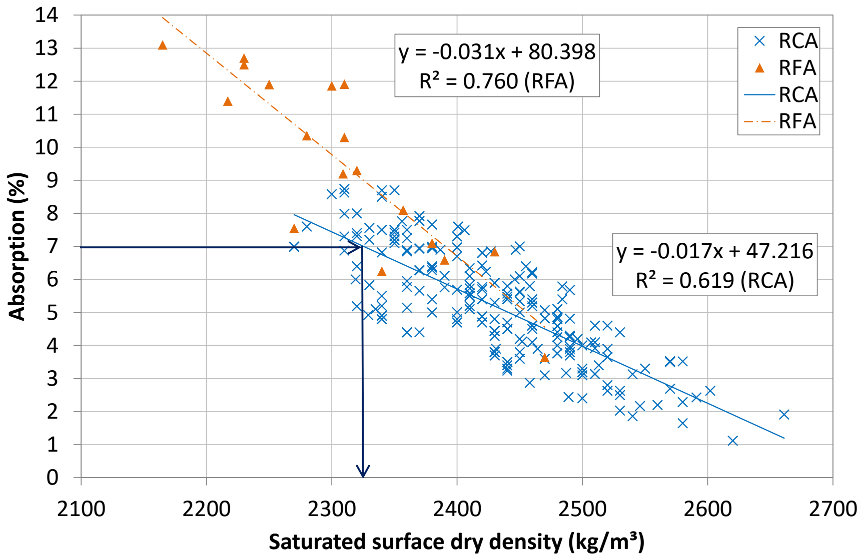


Figure II-7. Water absorption vs. Saturated surface dry density

Note: RCA (recycled coarse aggregate); RFA (recycled fine aggregate)

Figure II-7 shows that recycled coarse aggregate with water absorption values under 7% corresponds with density values over 2300 kg/m³.

2.2.6 Abrasion resistance

Researchers use different methods to measure the hardness and abrasion resistance of aggregates [DOMI09, KOU08, KONG10]. However, the Los Angeles abrasion test is one of the most common methods and hence, the Los Angeles coefficient is the value that has been used to study recycled aggregate behaviour.

In general, recycled concrete aggregate shows higher Los Angeles values than natural aggregate because weight loss is due to two causes: loss of adhered mortar and loss of original aggregate [LOPE08].

Several researchers have observed that the resistance to crushing, impact and abrasion of recycled aggregates is relatively lower than that of virgin aggregates, due to the separation and crushing of the porous mortar coating from the recycled aggregate during testing.

Regarding parent concrete, again it depends on whether the main effect is the quantity of adhered mortar (low strength original concrete presents lower quantity of mortar) or its quality (low strength concrete presents more porous adhered mortar). Furthermore, this property is not only influenced by the water to cement ratio. For a given strength of parent concrete, the resistance to mechanical action decreases as the maximum aggregate size decreases. This can be attributed to the relatively larger surface area of smaller sized aggregates facilitating higher mortar coating, compared to larger sized aggregates. Finally, again, recycled aggregate obtained from concrete with a low water/cement ratio may exhibit a higher abrasion value than other from a concrete with a high water/cement ratio. This is due to the fact that the water/cement ratio of the original concrete is relatively less important than the abrasion loss value of the natural aggregate that it contains [ZEGA10].

Of course, again, a high number of crushing processes leads to better behaviour against impact and abrasion, due to the fact that these crushing processes reduce the size of the cement adhered mortar which is finally eliminated during the sieving process.

Figure II-8 shows the results of the Los Angeles coefficient as a function of maximum aggregate size. Ninety different datasets were considered in the database. It can be seen that this coefficient is influenced by aggregate size. As the aggregate size decreases, the Los Angeles coefficient increases (meaning a decrease in abrasion resistance). This is due to the fact that the fine fractions have a higher percentage of attached mortar than the coarse kind [BRAN15]. However, in this case, high scatter can be observed. This is due to the different qualities of original waste (also this property is influenced by the original aggregate) and the number of crushing processes used in the plant.

The values obtained from the literature range generally between 25% and 40%, with an average value of 32%.

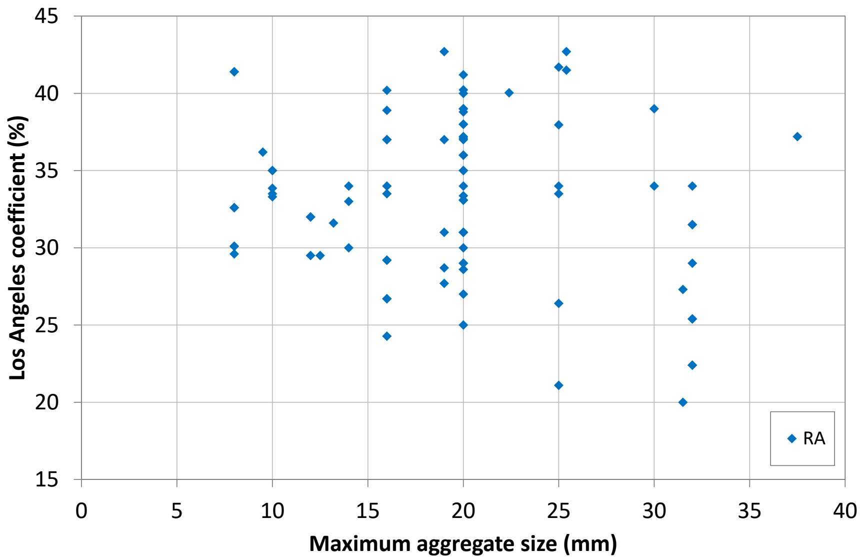


Figure II-8. Los Angeles coefficient vs. Maximum aggregate size

Note: RA (recycled aggregate)

In general the standards do not establish additional requirements for the Los Angeles coefficient. Some of them propose other types of tests to evaluate aggregate abrasion resistance [ACHE06, WBTC02].

Figure II-9 (with fifty-eight datasets) shows the relationship between the Los Angeles coefficient and the water absorption capacity of recycled concrete aggregate. Figure II-9 shows that recycled coarse aggregate with water absorption values under 7% results in a Los Angeles coefficient under 42%.

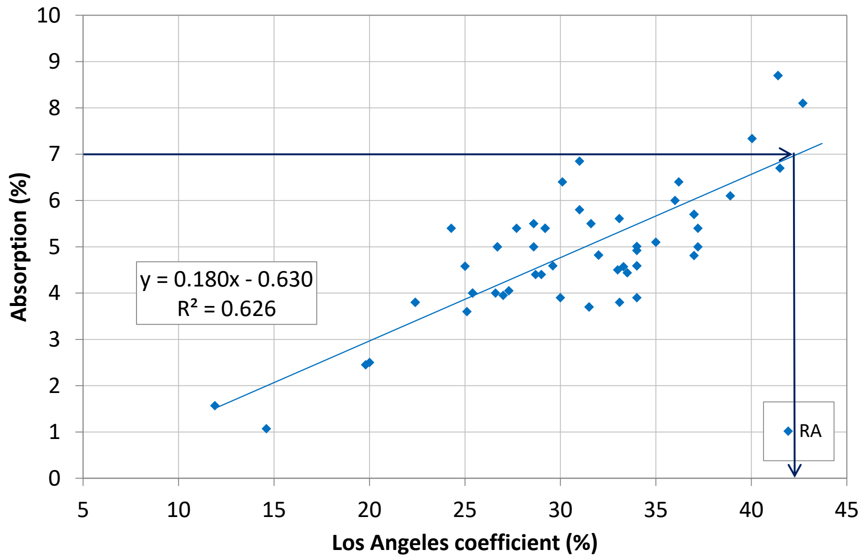


Figure II-9. Water absorption vs. Los Angeles coefficient

Note: RA (recycled aggregate)

Figure II-10 (with fifty-five datasets) shows the relationship between the Los Angeles coefficient and density of recycled concrete aggregate. In this case, as the density values decrease, the Los Angeles coefficient increases. Figure II-10 shows that recycled coarse aggregates with Los Angeles coefficient values under 42% correspond with density values over 2410 kg/m³.

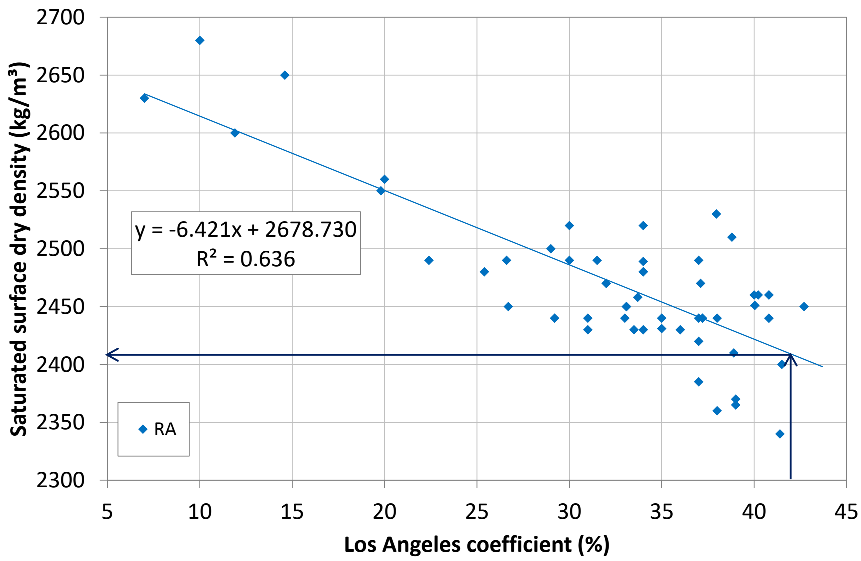


Figure II-10. Saturated surface dry density vs. Los Angeles coefficient

Note: RA (recycled aggregate)

2.3 Influence of recycled concrete aggregate properties on concrete compressive strength

Figure II-11 shows the relationship between the cube compressive strength of recycled concrete and the water/cement ratio (w/c) as a function of the percentage of replacement of natural coarse aggregate with recycled coarse aggregate, and taking into account the recycled aggregate water absorption. In Figure II-12, the same relationship is analysed as a function of saturated surface dry density. It is important to note that the cement strength grade, in all cases, was 42.5 MPa and that the recycled concrete was made by pre-soaking or adding additional water during the mixing procedure (in general compensating up to 80% of recycled concrete coarse aggregate absorption).

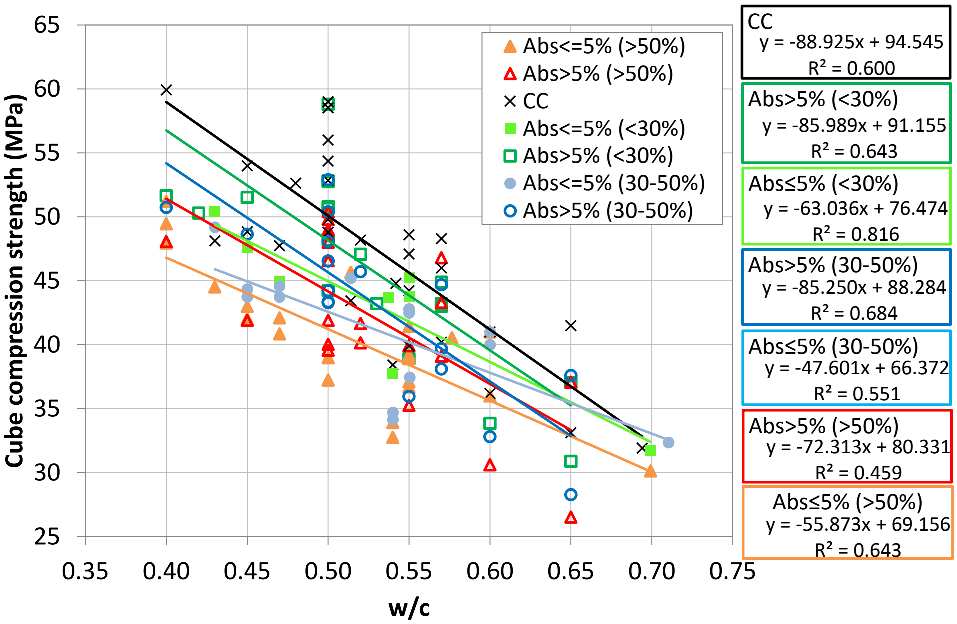


Figure II-11. Cube compression strength vs. water/cement. Effect of recycled aggregate percentage and water absorption

In both figures, there are two groups of straight lines: one related to aggregate with absorption over 5% (Figure II-11) or density under 2450 kg/m³, Figure II-12 (values determined according to Figure II-11) ("low density recycled aggregate"-LDA) and the other showing aggregates with absorption under 5% or density over 2450 kg/m³ ("high density recycled aggregate"-HDA).

In each group, there are four straight lines according to the replacement percentage: replacement of 0% or control concrete, replacement under 30%, replacement between 30% and 50%, and finally replacement over 50%.

Although some scatter can be observed, in both figures the tendency is the same, which allows the following conclusions to be made.

Firstly, it can be seen that the control concrete always shows the highest strength. Additionally, in each group (HDA and LDA), the lines corresponding to high replacement percentages are always below those corresponding to low replacement percentages. This means that as the replacement ratio increases the compressive strength decreases. However, the differences are greater for lower water/cement ratios than for higher. In fact, as the w/c ratio increases the three lines of each group tend to approach each other. Therefore, for a high w/c (over 0.6), the influence of the presence of recycled aggregates on compressive strength is not significant. In these cases, the effect of the low quality of the cement paste is more significant than the presence of the recycled aggregates.

Regarding each group of lines, HDA and LDA, it can be seen that, in general, the HDA are under the LDA, which means that as the density of the recycled aggregates increases, or the water absorption capacity decreases, the compressive strength decreases.

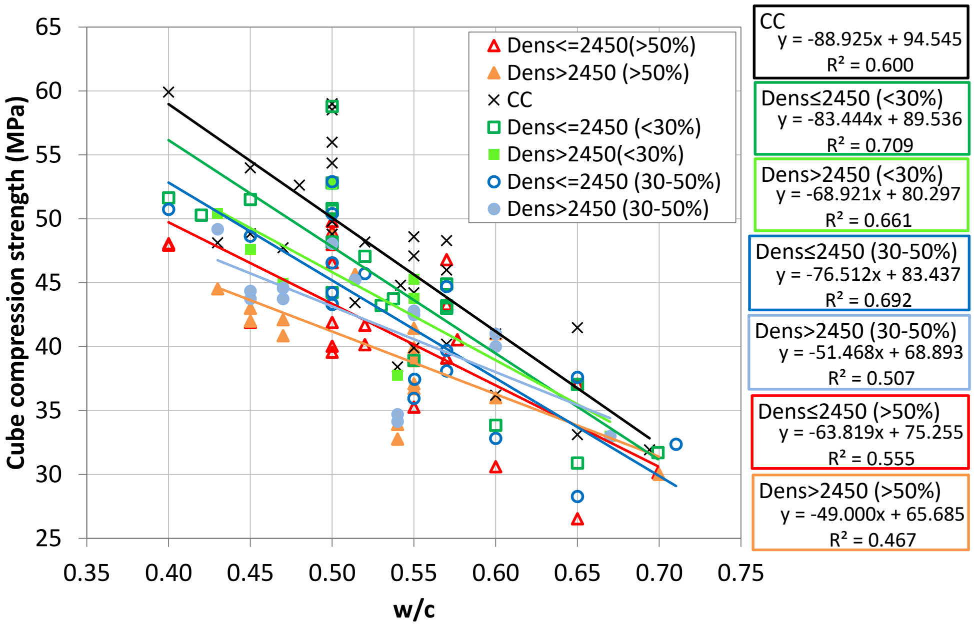


Figure II-12. Cube compression strength vs. water/cement ratio. Effect of recycled aggregate percentage and saturated surface dry density

The higher strength achieved with the low density or high water absorption aggregate group (LDA) compared with that of the high density or low water absorption group (HDA), is probably due to the different degree of bleeding developed. It is well known that when using pre-soaked recycled aggregates, the high water content inside the particles may result in bleeding during casting. The water inside the recycled aggregate particles may move towards the cement matrix, creating a region with an increased w/c ratio and high porosity. Furthermore, it should be remembered that recycled concrete has two interfacial transition zones (ITZ); one formed in the recycled aggregate (bond between original aggregate and old mortar) and the other newly created between the recycled aggregate (including old mortar) and the new cement paste. The bleeding process can weaken the bond between the recycled aggregate and the new cement matrix, which would weaken the strength of the concrete. When recycled aggregates have a high water absorption capacity (LDA) they can absorb a high amount of free water (when extra water is added) or retain a high amount of moisture (when pre-soaked aggregates are used). This fact would lower the initial w/c in the ITZ at early hydration. Newly formed hydrates would gradually fill this ITZ, which would effectively improve the interfacial bond between the recycled aggregate and the new cement paste. However, when recycled aggregates have a low water absorption capacity (HDA) they can’t absorb a high amount of free water or retain a high amount of moisture. In this case, the degree of bleeding is high, negatively affecting the ITZ and leading to a reduction in compressive strength [POON04a, ETXE06, GONZ11a].

Finally, again, when the w/c ratio is low the differences between the HDA and LDA line groups are significant, although as the w/c ratio increases these differences decrease. This means that when the w/c ratio is high (over 0.6), the quality of the ITZ between recycled aggregate (including old mortar) and new cement paste is not as significant as the low quality of the new cement paste, which is the “weak link in the chain”.

In short, Figure II-11 and Figure II-12 provide producers with useful expressions and correlations for designing recycled concrete. Taking into account recycled concrete coarse aggregate absorption (or density) and the replacement percentage, they can select a target strength, in average values, and obtain the water/cement ratio for recycled concrete production.

2.4 Final remarks

The database has made it possible to analyse the different properties of recycled concrete aggregate (aggregate recycled from concrete waste), such as density, water absorption, Los Angeles coefficient, etc. Relationships between these properties and also between some of them and the compressive strength of recycled concrete have been established. This has provided a design methodology for structural recycled concrete based on the physical-mechanical properties of recycled concrete aggregate. This methodology allows producers to establish the water/cement ratio necessary for a recycled concrete target strength, as a function of the quality of the recycled concrete coarse aggregate and the replacement percentage, whenever the mixing procedure used is the pre-soaking or compensation method (the extra water method).

Therefore, the following conclusions can be made:

- The main difference between natural aggregate and the recycled concrete aggregate is the adhered mortar. The presence of this material decreases with the number of crushing processes, the size fraction and the original waste quality.
- The recycled concrete aggregate presents a generally low quantity of impurities, with most standards establishing a minimum material from concrete waste of 90%.
- The recycled concrete coarse aggregate grading is similar to that of natural coarse aggregate. However, recycled sand is generally thicker than the natural fine aggregate. Furthermore, authors agree with the fact that the superficial roughness of recycled concrete aggregate is high, which also affects the loss of workability in concrete.
- The saturated surface dry density of recycled concrete aggregate is lower than that of natural aggregate and decreases with the maximum size. When recycled concrete coarse aggregate is analysed, the average density is 2437 kg/m³. When the recycled sand density is considered, the average value is 2312 kg/m³. All authors agree with the fact that the adhered mortar is the cause of this decrease.
- The natural aggregate water absorption usually ranges between 0% and 4% while the recycled concrete aggregate value is between 1.65% and 13.10%. Again, the water absorption increases as the maximum aggregate size and density value decrease. Using this database it has been seen that recycled concrete coarse aggregate with water absorption values under 7% provides saturated surface dry density values over 2300 kg/m³.
- The Los Angeles coefficient of the recycled concrete aggregate is higher than that of natural aggregate. It increases with water absorption and decreases with density and maximum aggregate size. Using the database it has been seen that recycled concrete coarse aggregate with water absorption values under 7% provides a Los Angeles coefficient under 42%.
- Regarding compressive strength, it has been concluded that as the replacement percentage increases the compressive strength decreases. However, when the w/c ratio is over 0.6, the influence on compressive strength of the presence of recycled aggregate is

not significant. In these cases, the effect of the low quality of the new cement paste is more significant than the presence of the recycled aggregate.

- Finally, the properties of recycled aggregates (water absorption and density value) and also the mixing process chosen to compensate their high water absorption (adding extra water or pre-soaking before mixing) influence the quality of the ITZ and therefore the concrete compressive strength. When recycled aggregates have a low water absorption capacity they can't absorb a high amount of free water and retain a high amount of moisture. In this case, the degree of bleeding is high and so the ITZ is negatively affected which leads to a reduction in compressive strength. However, when recycled aggregates have a high water absorption capacity they absorb a high amount of free water and retain a high amount of moisture. In this case the ITZ is effectively improved and the compressive strength is high.

Therefore, it can be concluded that when recycled aggregate water absorption is low (in this study under 5%), pre-soaking or adding extra water to avoid loss in workability will negatively affect concrete compressive strength (due to the bleeding effect and through the ITZ), whereas when water absorption is high this does not occur and both of these correcting methods can be accurately used.

Finally, knowing how the recycled concrete aggregate (both percentage and quality) and the mixing procedure (pre-soaking or adding extra water) influence the recycled concrete strength of different categories (high or low water to cement ratios), enables recycled concrete to be manufactured in an accurate manner.

3 RECYCLED CONCRETE (RC)

The use of recycled aggregates from demolished concrete structures dates back to the time of World War II in Europe. Earlier it had been used as unbound sub-base materials for pavement [BEHE14]. Nowadays it is being also used for construction purposes [PAIN11]. Its use in concrete has generated interest in civil engineering construction regarding sustainable development as it is the means of achieving a more environmentally friendly concrete (Figure II-13).

Concrete made up of recycled aggregates in terms of fine or coarse or both fractions processed from C&D waste, either as a partial or 100% replacement of conventional natural aggregates, is known as recycled concrete (RC).

3.1 Materials

Aggregates

Regarding natural aggregates, both coarse and fine fractions are used to produce recycled concretes, fulfilling the same requirements as in conventional concretes. Rounded from riverbeds or crushed natural aggregates can be used and their characteristics must allow to produce concretes with adequate strengths and durability.

Regarding recycled aggregates, they are extracted from the debris generated in the demolition of concrete structures and other construction debris such as waste concrete, rejected precast concrete members, broken masonry, concrete road beds and asphalt pavement, leftover concrete from ready mix concrete plants and the waste generated from different laboratories [BEHE14].

Figure II-13. Life cycle for sustainable development in construction industry

The integral technique behind recycling process includes the breaking of demolished concrete to produce smaller size fragments by subjecting to a series of performances such as removal of contaminants (reinforcement, wood, plastic etc.), different stages of screening and sorting (Figure II-14). Higher quality aggregates can be also processed in steps with time and effort involved in stock piling, crushing, pre-sizing, sorting (pre-crushing and post-crushing), screening and contaminant elimination depending on the level of contamination and the application for which the recycled materials will be used [SILV14, PAIN10b].

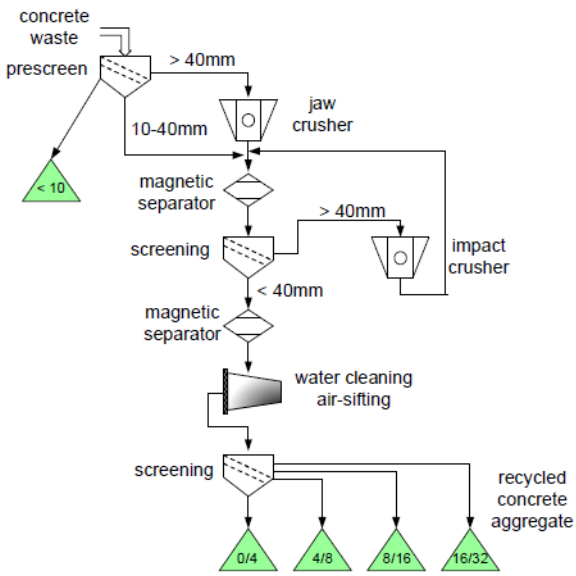


Figure II-14. Recycling procedure [MARI10]

Demolition debris can be crushed by several crushing devices such as jaw crusher, hammer mill, impact crusher, and cone crusher or manually by hammer [SILV14]. Different crushers have different consequences on the physical and mechanical properties of recycled aggregates depending on the effectiveness of crushing processes and consequently it also affects the concrete performance.

Recycled aggregate typically processed by the crushing of parent or old concrete such as demolished waste concrete is regarded as recycled concrete aggregate. The crushing of concrete waste to produce recycled concrete aggregate offers the dual benefits of diverting concrete waste from landfills and reducing the demand for natural aggregates [BUTL13].

To sum up what was thoroughly analysed in the previous section, recycled concrete aggregates mainly differ from natural aggregates in that they are composed by two different materials: natural aggregate and adhered cement mortar. This adhered mortar is the origin of the worse properties of recycled aggregates: lower density and higher absorption, Los Angeles abrasion resistance coefficient and sulphate content.

The recycled aggregate properties have a negative influence on recycled concrete quality, mainly affecting to concrete properties related with strain (elasticity, shrinkage, and creep), also durability, and to a lesser extent strength [JUAN09].

The fine fraction (< 4 mm) is not used due to its high absorption capacity, which can produce large shrinkage and permeable cement paste [ETXE07a]. For that, in Europe, the use of coarse fraction is only allowed to reduce the differences between a recycled concrete and a conventional concrete.

Cements, additions and admixtures

The type of cement for recycled concretes will be the same as for conventional concretes, only depending on the application. Different additions can be also used in the same way. The use of admixtures that modify rheology is recommended to improve workability in recycled concretes with replacement percentages higher than 20%, compensating the high absorption of recycled aggregate when it is used in dry-state conditions.

3.2 Mix proportions

In general, all previous investigations have proportioned recycled concretes based on conventional mix proportioning methods, considering recycled concrete aggregate as a homogenous material, similar to natural aggregate, but with its particular absorption capacity and density. The existing literature shows that standard methods used for the mix design of conventional concrete can be used for the design of recycled concrete [BHIK10].

A fundamental parameter of recycled concrete mix proportions is the water to cement ratio that affects workability and compressive strength. For this reason, an exhaustive control of absorption, moisture and density of recycled aggregate is necessary. Consequently, recycled concrete mixes proportioned according to conventional aggregate replacement methods have invariably resulted in inferior physical and mechanical properties compared to the original concrete, although in some investigations recycled concrete with compressive strength equal to the associated original concrete has been achieved by adjusting the water to cement ratio [FATH10].

Fathifazl et al. [FATH10] have proposed a new method, dubbed the “equivalent mortar volume” (EMV) method, which allows to determine the proper amount of recycled concrete aggregate and other mix components to achieve the same fresh and mechanical properties as a companion mix made with only natural aggregates. These authors concluded that recycled concrete mixes proportioned by the proposed “EMV” method have higher slump, fresh and hardened density, and elastic modulus and comparable compressive strength to recycled concrete mixes with almost identical water and cement contents but proportioned by conventional mix design methods.

Water content

As aforementioned, water absorption is higher in recycled aggregates than in natural aggregates due to the adhered mortar. So, recycled concrete produced with recycled coarse aggregates and natural fine aggregates is considered to require between a 5% and a 10% more of water than conventional concretes to achieve the same workability [ACHE06].

To obtain the same workability after the first 30 min, Malešev et al. [MALE10] found that recycled concrete with 50% of recycled coarse aggregate requires about 10% more total water quantity in comparison to the reference conventional mix, and the corresponding value for recycled concrete with 100% of replacement percentage is about 20%.

Cement content

Recycled concretes need a higher cement content in their mix proportions to obtain the same workability and strength than conventional concretes [JUAN04].

Etxeberria et al. [ETXE07b] concluded that medium compression strength (30–45 MPa) concrete made with 25% of recycled coarse aggregate achieves the same mechanical properties as those of conventional concrete employing the same quantity of cement and the equal effective water to cement ratio. However, medium compressive strength concrete made with 50% or 100% of recycled coarse aggregate needs 4–10% lower effective water to cement ratio and 5–10% more cement than conventional concrete to achieve the same compression strength at 28 days.

Bairagi et al. [BAIR93] stated that, compared to the natural aggregate concrete, the additional cement demand for the recycled concrete lies between 8% and 13%, the higher value being for higher grades of concrete.

González and Martínez [GONZ05] found a cement content increase of 6.2% when 50% of recycled coarse aggregate is used to achieve similar strength (around 30 MPa at 28 days) and similar workability (slump between 6 and 9 cm) in both types of concretes (conventional and recycled).

Admixtures

Supplementary cementing materials such as silica fume, fly ash and blast furnace slag can be used as partial replacement for Portland cement in recycled concretes, with similar positive effects as in conventional concretes.

González and Martínez [GONZ08] established that the addition of 8% silica fume to mixes containing recycled aggregates was found to be beneficial in terms of compressive strength. In the same way, few differences were observed in the tensile splitting strength of all the concrete types at various ages.

Sani et al. [SANI05] concluded that, in general, the use of recycled aggregate as a total replacement for natural aggregate causes an increase of the total porosity and a reduction in mechanical strength that can be attenuated by fly ash addition.

In the work of Poon et al. [POON07], the replacement of cement by 25% fly ash increased the slump of concrete mixes with and without recycled aggregates. It also had beneficial effects in reducing the bleeding rate and bleeding capacity, with only minimal negative effects on concrete strength at or before 28 days, but positive effects on the strength at 90 days.

Tangchirapat el at. [TANG10] observed that the use of high fineness of fly ash to replace Portland cement type I in the amounts of 35 and 50% by weight of the binder resulted in 15 to 30 min slower slump loss of concrete than recycled concrete without fly ash. Moreover, the slump loss of recycled concretes containing 35% high fineness of fly ash by weight of the binder was equivalent to that of natural aggregate concrete. These authors also concluded that the use of high fineness of fly ash in recycled concrete yielded greater compressive strength than recycled concrete without high fineness of fly ash. Concretes made from 100% recycled coarse aggregate and river sand had compressive strengths equivalent to or greater than conventional concrete at 28 days when Portland cement was replaced by high fineness of fly ash at 20 to 35% by weight of the binder. The use of high fineness of fly ash did not affect the splitting tensile strength of recycled aggregate concrete and recycled concretes with and without high fineness of fly ash had lower modulus of elasticity values than conventional concretes.

The results of Berndt [BERN09] indicated that concrete mixes containing 50% replacement of cement with blast furnace slag gave the best results in terms of mechanical properties and durability when either natural or recycled concrete aggregate was used. On the other hand, this author concluded that it cannot be assumed that all fly ash sources will necessarily improve the properties of concrete at high replacement levels of cement and that detailed testing of specific materials and mix proportions is recommended before use in construction projects.

3.3 Mixing procedure

As aforementioned, the greatest distinctive features of recycled aggregates compared to natural aggregates is their lower density and higher absorption capacity, due mainly to the adhered mortar.

A high absorption capacity influences fresh concrete properties. It is necessary to control accurately the casting process, with the aim of controlling the effective water to cement ratio [PEPE16]. Thus, the volume of mixing water is determined before concrete production, in order to maintain constant the water amount reacting with the binders (effective water). The volume of mixing water is composed of the effective water and the water absorbed by the aggregates at concrete production (effective absorption capacity) [GONZ16]. Then, to obtain the desired workability of recycled concrete, it is necessary to add a certain amount of water to saturate recycled aggregate, before or during mixing (Figure II-15).

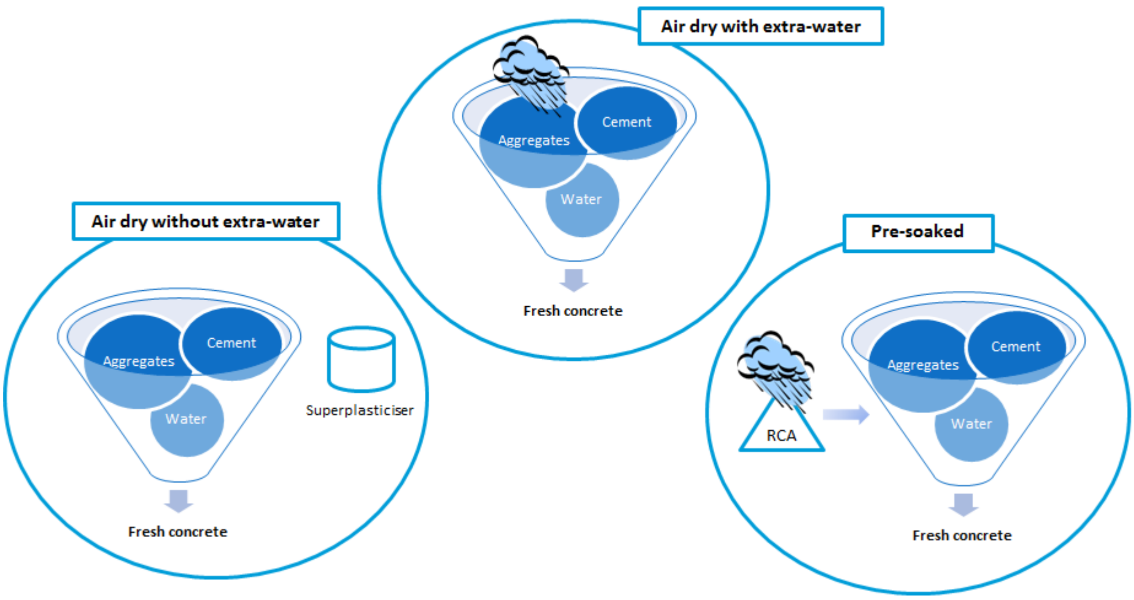


Figure II-15. Possible moisture states of recycled aggregate and mixing procedures

This has given way to a number of studies in which essentially two alternatives are described: to work with dry aggregates while increasing the amount of water incorporated in the mix, or pre-wetting them. The latter has generated several processing options: pre-soaking for 24 h, pre-soaking for 10 min, or sprinkling (Table II-1).

Working with dry aggregates while increasing the amount of water incorporated in the mix is known as the mixing water compensation. The amount of water added depends on the initial water content and effective absorption of recycled aggregates during the mixing period. Potential water absorption and absorption evolution over time should be also known in order to predict the water to cement ratio after the mixing period [FERR11]. In this case, it is well-known that the initial moisture content has influence on the absorption during the mixing process influencing, then, some recycled concrete properties [PELU09, POON04b]. This method has the advantage of making it possible to produce both recycled and conventional concretes in a similar way.

Pre-soaking for24 h implies working with saturated aggregates. Some authors consider that this system introduces excess water with a detrimental effect on recycled concrete strength [POON04b]. Nevertheless, Oliveira and Vázquez [OLIV96] stated a slight decrease in the compressive strength of concrete made from both dry and saturated recycled aggregates.

Table II-1. Typical pre-soaking methods of recycled aggregates

Reference	Pre-soaking methods	Reference	Pre-soaking methods
[CORI10a]	Saturated surface dry	[GOME02]	20 min
[PELU09]	10 min (and to drain 10 min)	[BARR97]	Semi-saturated
[POON04b]	24 h (saturated surface dry)	[ETXE07a]	Humid condition
[OLIV96]	Saturated/Semi-saturated	[EVAN07]	10/20 min
[CASU08]	24 h (and to drain 1 h)	[DEBI10]	24 h
[ETXE07b]	Sprinkling (semi-saturated)	[VILL08]	24 h
[RAHA07]	Saturated surface dry	[ORTE10]	24 h
[GONZ11b]	10 min	[MAIO03]	24 h
[BERN09]	24 h	[JUAN04]	10 min
[ANGU10]	10 min	[CORI11b]	Saturated surface dry
[CORI11a]	Saturated surface dry	[FERR11]	5 min

Pre-soaking for 10 min consists of pre-wetting recycled aggregates considering that 70-80% water absorption in coarse fractions is guaranteed and this 10 min period would reduce the degree of bleeding [GONZ11b].

In the system of sprinkling, the drawback is the need for a large surface on which aggregates can be appropriately extended to ensure a uniform distribution of water.

3.4 Fresh-state properties

The physical properties of recycled concrete are affected by the replacement percentage of recycled concrete aggregate. This aggregate can influence the properties of fresh concrete due to its greater angularity, surface roughness, absorption and porosity.

The use of recycled concrete aggregate in dry-state conditions reduces the workability of recycled concrete when the same water to cement ratio as in conventional concrete is maintained. This is mainly attributed to the absorption of recycled aggregates. Other physical characteristics of recycled aggregate particles have also influence in the increase of water demand. Their rough texture increases the harshness of concrete mix, and thus decreases its workability. In addition, a deficient gradation of recycled aggregate or its change during mixing by the generation of fines contribute to decrease the workability of concrete. The loss of cement paste into the surface pores of recycled aggregates also decreases workability [SAFI11].

The degree of decrease in recycled concrete workability increases with the increase in the recycled aggregate percentage. Therefore, additional water is required for recycled concrete to obtain the same workability of conventional concrete [SAFI13].

Then, in order to achieve a target workability, different options are possible: quantify the extra water that should be added during mixing, using the recycled aggregate in saturated conditions or adding a significant quantity of superplasticiser.

Similar slump can be obtained with comparable quantities of free water, indicating that the water requirement for a given slump is not affected by the type of aggregates or by the crushing age. It was noted that when there is an insufficient amount of fines in recycled aggregates, some quantities of natural sand are still needed in order to maintain proper workability and cohesiveness [KATZ03].

Moreover, the higher absorption of recycled aggregate can lead to a rapid loss of workability limiting the time needed for placing concrete.

On the other hand, it is well studied that the density of recycled concrete decreases with the replacement percentage, mainly due to the adhered mortar of recycled aggregates. The air content of the fresh concrete containing recycled aggregates is slightly more variable and often up to 0.6% higher than the air content of fresh conventional concrete. This would be caused by the air that is entrained and entrapped in the reclaimed mortar of recycled concrete aggregates [SAFI11].

3.5 Hardened-state properties

In general terms, it can be stated that the quality of recycled concrete is lower than that of conventional concrete with the same mix proportions. The compressive and splitting tensile strengths, and modulus of elasticity decrease when the percentage of recycled aggregate increases, and the shrinkage and creep increase. These variations are mostly due to the adhered mortar. Despite the differences in properties between recycled and conventional concretes, the concrete containing recycled aggregates can be properly designed and successfully used in the common applications of civil engineering.

Table II-2. Effect of recycled concrete aggregate on RC hardened properties (from [SAFI13])

Property	Range of changes
Dry density	5-15% less
Compressive strength	0-30% less
Splitting tensile strength	0-10% less
Flexural strength	0-10% less
Modulus of elasticity	10-45% less
Drying shrinkage	20-50% more
Creep	30-60% more
Bond strength	9-19% less
Porosity	10-30% more
Permeability	0-500% more
Water absorption	0-40% more
Chloride penetration	0-30% more
Thermal expansion	10-30% more

Compressive strength

Overall, as the replacement level increases, there is a decrease in compressive strength, the extent of which mainly depends on the recycled aggregates' type, size and origin [SILV15a].

It was also found that recycled concrete produced with rounded natural aggregates presents a completely different strength behaviour from recycled concrete produced with crushed natural aggregates. The former may not show a decrease in the compressive strength, and it may even produce an increase of up to 15% [LASE16].

For a given water to cement ratio, there will be a higher strength loss as the quality of recycled aggregate worsens. This effect is more noticeable for lower water to cement ratios since the ultimate compressive strength becomes more dependent on the strength of recycled aggregate, instead of that of the cement matrix [SILV15a].

The strength characteristic of recycled concrete depends on the quality of new interfacial transition zone (ITZ), when the quality of old ITZ is better than that of new ITZ. On the other hand, the strength characteristic of recycled concrete depends on the quality of old ITZ, when the quality of new ITZ is better than that of old ITZ [RYU02].

At 28 days, the compressive strength of 100% recycled coarse aggregate concretes, can show reductions up to 30% [SEAR15]. However, low replacements percentages (25%) does not influence much on compressive strength of concrete [CHAK11].

It was observed that, even though recycled concrete may have lower 28-day compressive strength with increasing recycled concrete aggregate content, over a long period of time, recycled concrete may demonstrate greater strength development than the corresponding conventional concrete. This was explained by latent cementitious properties of the mortar adhered to old aggregates [SILV15a].

Splitting tensile strength

The literature review shows a consensus in that, as the replacement level increases, the tensile strength decreases. Although there is a clear trend that the inclusion of recycled aggregate leads to lower splitting tensile strength when compared to that of the control concrete, in a few cases recycled concrete exhibited similar or even slightly greater strength. It is possible that the bond strength in the interfacial transition zone, between the old adhered mortar and new cement paste, improved due to the rough nature of recycled concrete aggregate [SILV14].

Several past investigations on recycled concrete showed that the effect of recycled aggregate content on splitting tensile strength is less than that on compressive strength [RAVI85, SAGO01, ETXE07a, GONZ11a]. Some authors in their studies have mentioned that the decrease in splitting tensile strength is up to 10% [RAHA07]; however, some researchers have obtained higher values than these proposed reductions. It was found a decrease of 5-15% for a replacement percentage of 50% and of 15-25% for the 100% when recycled concrete is produced with crushed natural aggregates [LASE16], whereas no significant differences were observed when recycled concrete is manufactured with rounded natural aggregates.

Flexural strength

Flexural strength of recycled concrete was found to slightly decrease with higher replacement levels of RCA, likely due to the reduced bond performance of the interfacial transition zone at the residual and new mortar interface, as well as the reduction in particle interlocking experienced with the increased residual mortar content [SUCI16].

However, some authors have reported that there was no significant difference found in flexural strength of recycled concrete even if containing 100% recycled aggregate in comparison to that of conventional concrete [BEHE14].

In different literature, it has been found that the flexural strength of recycled concrete decreased up to 10% [AJDU02, MALE10]. Bairagi et al. [BAIR93] also observed a significant difference in the flexural strength of recycled concrete at different w/c ratios than conventional concrete.

Modulus of elasticity

Substitution of natural aggregate by recycled aggregate also affects the modulus of elasticity. However, recycled aggregate content has more effect on the modulus of elasticity than on the compressive strength due to its porous nature, low density and weak bond between old ITZ and new ITZ due to presence of more capillary voids and cracks. Like compressive strength, similar trend has also been observed for modulus of elasticity with degree of substitution of recycled aggregate. Modulus of elasticity of recycled concrete decreases considerably and it reduces with the increase in recycled aggregate [PADM09, CHAK11].

It is found that the modulus of elasticity of recycled concrete with 100% recycled aggregate can be lowered up to 45% than that of natural aggregate concrete [XIAO05], although this will be an upper limit since many authors in their studies have obtained lower reductions compared to the modulus of conventional concrete [BHIK10, FERR11, GONZ11b].

Creep and shrinkage

Most of the current studies in the recycled concrete field deal with short-term analysis related to basic properties and structural performance, and only a few have studied the long-term behaviour [DOMI10, FATH11, BOGA15, BRAN15, MANZ13, TAM15, SEAR16]. The conclusions reached in these studies suggest that, in general, long-term strains are higher than those obtained with conventional concrete. These deformations are produced by the shrinkage effect when the concrete is under no load, and effect of creep and shrinkage when subjected to load. Therefore, it is necessary to know the shrinkage strain and creep coefficient in order to analyse the long-term behaviour of structural recycled concrete.

Some authors have stated that shrinkage increases between 18% and 80% when analysing concretes made with 100% of recycled aggregates [DOMI10], with these percentages being considerably lower when replacement ratios of 20-30% are used [DOMI10, CORI10a]. Most current research states that shrinkage has a linear correlation with the replacement percentage [DOMI10, FATH11, BRAN15, MANZ13, TAM15, SILV15c]. However, works dealing with its time-dependent development are scarce. Some of them seem to reveal a delayed development of shrinkage at early ages due to the high water absorption of the recycled aggregates, especially when they are used in saturated conditions [CORI10a, SILV15c, PEDR14b]. Furthermore, as it is well known, conventional concrete shrinkage mainly occurs during the first year, after which asymptotic trending is shown. In this regard, Seara et al. [SEAR16] measured the shrinkage beyond one year in order to experimentally determine if recycled concretes have the same behaviour as the conventional kind. This work showed that over 80% of the final shrinkage (at t = 1042 days) has occurred in the first year and then tends to stabilize over time.

Also, greater creep strains are produced in concrete with recycled concrete aggregates compared to conventional concrete with increases of 5-25% for low replacement percentages of recycled coarse aggregate (15-30%) and 56% for high replacement ratios [DOMI10, GOME02, MASA06, MANZ13, FATH11, SEAR16]. This effect is attributed to the attached mortar content, which reduces the quality of the recycled aggregates [MASA06] and varies the w/c ratio [DOMI10, GOME02, MANZ13, FATH11]. However, the experimental results obtained from other research show a different trend for recycled concrete creep, which is reduced in 17-20% compared with that of the conventional concrete [MANZ13, ADJU02]. Based on this literature review, it can be noted that further research is required to obtain a common criteria for the prediction of creep strains.

In addition, different authors [CORI10a, PEDR14b, SEAR16] have pointed out that the internal curing effect influences recycled concrete properties at early ages, although no relationship is defined with the creep behaviour.

Lastly, although some research has proposed a modified expression [FATH11, SILV15c, SEAR16] for predicting recycled concrete shrinkage and creep, there is no unified proposal involving both the replacement percentage and the specific behaviour of recycled concrete at early ages. Some authors point out a delayed development in time-dependent mechanical strengths, which also has a significant influence on the time-dependent properties of recycled concretes. However, this phenomenon is not included in the current predictions for structural recycled concretes.

Stress-strain curve

The recycled coarse aggregate content has a significant influence on the strain properties of concretes. The longitudinal strain of recycled concretes increases with the percentage of recycled coarse aggregate used, so that the slope of the stress–strain curves decreases. This means that the values of modulus decrease. It also means that the strains, particularly the peak and ultimate strain, increase [XIAO05, GONZ11b]. This effect can be attributed to attached mortar and the weak paste-aggregate interface.

Bond strength

The bond strength of recycled concretes is lower than the one of the conventional concretes with the same dosage, and it declines with the increase of recycled aggregate content showing a behaviour similar to compressive strength.

The time-dependent development of bond strength also follows the same trend as compressive strength. From 7 to 28 days, recycled concretes undergo a slightly higher increase than conventional ones. From 28 to 365 days, bond strength variation is barely noticeable [SEAR14].

The shape of the bond stress-slip curve changes with the recycled aggregate content. Slip values obtained at any bond stress value are greater in recycled concretes than in conventional ones, and increase as recycled coarse aggregate content raises. This increment is also significant for small replacement ratios (even 20%), which influences crack control and tension stiffening of recycled concretes. Therefore, the normalized bond stress at a fixed value of slip decreases when replacement percentage of recycled aggregate increases. The decline of bond stress at small slips of recycled concrete affects mainly serviceability conditions, especially crack control and tension stiffening. By increasing the replacement percentage of recycled aggregate, the load at serviceability state limit tends to lessen [SEAR15].

3.6 Durability

The durability of recycled concrete cast with the same water to cement ratio, is lower than that of the conventional concrete due to the higher porosity of recycled aggregates. However, in low water to cement ratio concretes, the low porosity of the new paste is predominant so the advance of aggressive agents is delayed, obtaining a similar behaviour for the control and recycled concretes [THOM13].

The water absorption of concrete depends on the quantity of recycled aggregate. The amount of absorbed water proportionally increases with the increase of recycled aggregate content. Water absorption depends on the porosity of cement matrix in the new concrete and porosity of cement matrix of the recycled concrete: if recycled aggregate is produced from low porosity waste concrete, water absorption of the new concrete depends on the achieved structure of the new cement matrix [MALE10].

The quality of recycled concrete is generally inferior to that of conventional concrete. Recycled concrete aggregate contains not only the original aggregate, but also hydrated cement paste adhered to the surface of this aggregate. This paste makes recycled aggregate more porous than natural aggregate. The higher porosity of recycled concrete aggregate leads to a higher porosity and water absorption in concrete [SAFI11].

The permeability of recycled concrete is higher than that of conventional concrete and increases with the increase in the replacement percentage. The water to cement ratio and the quality of the recycled aggregate affect the concrete permeability. The permeability increases as the water to cement ratio increases and as adhesive strength of mortar of the recycled aggregate decreases [RYU02]. Reducing the water to cement ratio in a certain range, adding admixtures such as fly ash or using a two-stage mixing approach can improve impermeability [XIAO14].

The resistance to the freeze-thaw test was shown to be particularly sensitive for detecting differences in concretes with different levels of moisture retention in aggregates. The poor result of concretes with saturated and dry recycled aggregates and the good result of those made from semi-saturated aggregates can be explained as being caused by formation of a more solid and denser interface in these conditions. This fact is reflected somewhat in the mechanical properties, but quite clearly in the durability tests [OLIV96].

There is still no generally accepted conclusion regarding the difference in carbonation resistance between recycled concrete and conventional concrete; adding slag, steel slag, reasonable control of water to cement ratio, etc. can improve carbonation resistance [XIAO14].

The abrasion resistance and sulphate resistance of recycled concrete are lower than those of conventional concrete [XIAO14].

4 SELF-COMPACTING CONCRETE (SCC)

Self-compacting concrete (SCC) is a new class of high performance concrete that can spread readily into place under its own weight and fill restricted sections as well as congested reinforcement structures without the need of mechanical consolidation and without undergoing any significant separation of material constituents [HWAN06] (Figure II-16).

Figure II-16. Self-compacting concrete (SCC)

The necessity of this type of concrete was proposed by Okamura in 1986 in order to achieve more durable concrete structures independent of the quality of construction work and by improving the quality of the placed material [OKAM03] (Figure II-17).

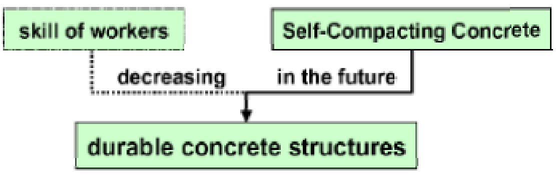


Figure II-17. Initial necessity of SCC [OKAM03]

The removal of the need for compaction of concrete reduced the potential for durability defects due to an inadequate vibration process. The SCC use was also found to offer economic, social and environmental benefits over traditional vibrated concrete construction. These advantages included:

- Decrease in construction cost due to labour reduction.
- Reduction in construction time.
- Simplification of the casting process as no vibration is needed.
- Improvement of working conditions through less noise hazards.
- Ability to cast congested and complex structural elements in various shapes and dimensions that are not attainable by any other conventional techniques.
- Ability to cast hard-to-reach areas that represent difficulties to placement and consolidation.
- Improving appearance and quality of the finished surfaces and reduction in the occurrence of bugholes, honeycombing and other surface imperfections.
- Producing a better and premium concrete product.
- Larger variety of architectural shapes by using any form shape. This is one of the major advantage of SCC where it is possible to cast heavily reinforced elements and structures with a complicated geometry that otherwise are not attainable by any other conventional techniques.
- Higher durability of concrete structures.
- Lowering pumping pressures, and as a consequence, reducing wear and tear on pumps, i.e. extends their service life.
- Lowering the need for cranes to deliver concrete in buckets at the job site by facilitating concrete delivery through pumping.

One of the main drivers for the development of SCC technology was the reduction in the number of skilled site workers that the Japanese construction industry was experiencing in the 1980s. The use of SCC meant that less skilled labour was required for the placing and finishing of concrete.

SCC was developed from the existing technology used for high workability and underwater concretes, where additional cohesiveness is required. The first research publications that looked into the principles required for SCC were from Japan around 1989 to 1991. These studies concentrated upon high-performance and super-workable concretes and their fresh properties such as flowability, filling capacity and resistance to segregation.

In the second half of the 1990s, interest and use of SCC spread from Japan to other countries, including Europe. Some of the first research work to be published from Europe was at an International RILEM (International Union of Testing and Research Laboratories of Materials and Structures) Conference in London in 1996.

Sweden was the first country in Europe to begin development of SCC, and in 1993 the CBI (Cement and Concrete Research Institute) organised a seminar in this country for contractors and producers, leading to a project aimed at studying SCC for housing. Now, nearly all countries in Europe conduct some form of research and development into SCC.

One of the major obstacles to a more wide spread use of self-compacting concrete is to obtain further understanding of the importance of rheology on the final concrete quality [THRA10]. The effect of flow properties, casting technique, and mix composition on the final concrete quality is not well understood.

During the course of time, empirical test methods of different types and quality have been developed and used to give some kind of rheological description of the fresh concrete. It is stated that the empirical tests are very often operator-sensitive, in the sense that minor variations in the execution of the test, gives a different result. The same literature discusses the need for describing the rheological properties of fresh concrete in terms of fundamental physical quantities, not depending on the details of the apparatus with which they are measured [WALL11]. Viscometers and advanced rheometers are usually designed to be operatively insensitive, meaning that variations in the technique of carrying out the test, does not affect the results.

Therefore, it is clear that rheology is the logical tool to characterize and describe the flow behaviour, workability loss and stability of SCC, avoiding misinterpretations of the results from casting and production studies.

4.1 Rheology

4.1.1 Concrete rheology

Rheology has been properly defined as the study of the flow and deformation of materials, with special emphasis being usually placed on the former. In flow, elements of the liquid are deforming, and adjacent points in the liquid are moving relative to one another. All flows are resisted by viscosity. For a given velocity, the resulting force increases when the viscosity is increased, whereas for a given force, the velocity is reduced when the viscosity is increased [BARN00].

Simple shear flow is the continual movement of particles of liquid over or past each other and it can be visualised as the movement of hypothetical layers sliding over each other (Figure II-18). The gradient of the velocity in the direction at right angles to the flow is called the shear rate (sometimes called the velocity gradient or strain rate), and the force per unit area creating or produced by the flow is called the shear stress.

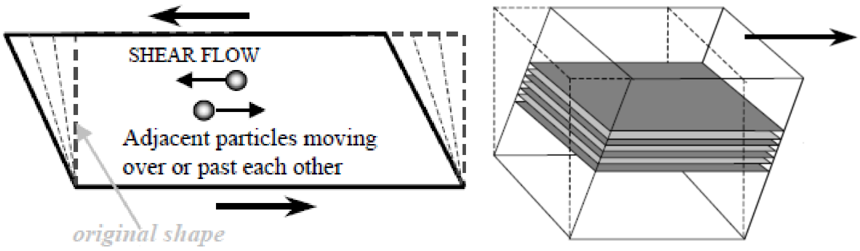


Figure II-18. Shear flow [BARN00]

Workability is defined as the property of freshly mixed concrete or mortar that determines the ease with which it can be mixed, placed, consolidated, and finished to a homogenous condition.

Fresh concrete workability is most often associated with the slump value measured using the European Standard EN 12350-2 “Testing fresh concrete. Part 2: Slump-test” [EN12350-2]. This is the most famous, oldest and currently most used empirical test and it gives only a single value, namely the slump value [WALL11]. However, the slump value does not completely describe the workability of some concrete mixes. For example, two shotcrete mixes with the same slump can require different pumping pressures. Also, two self-compacting concrete mixes with the same “slump” or slump flow values can have different flow capabilities when filling reinforced formwork [FERR03]. Therefore, concretes having the same slump can behave differently during placement because flow is not defined by a single parameter.

The flow behaviour of a material is characterised by the relation between shear stress (τ) and shear rate ($\dot{\gamma}$). A τ - $\dot{\gamma}$ diagram is often used for graphic representation. Usually, the shear stress is shown on the ordinate and the shear rate on the abscissa. These diagrams are referred to as flow functions or flow curves (Figure II-19).

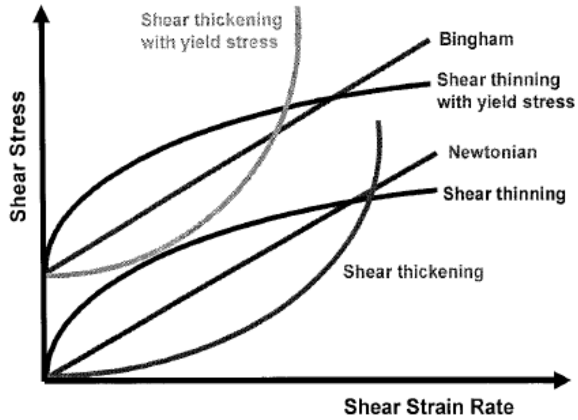


Figure II-19. Flow curves [HU05]

The result obtained with a viscometer or rheometer is always a flow curve. However, the viscosity function can be calculated based on the measured values.

Then, whenever a shear force is applied onto a fluid its velocity gradient has a relationship with it involving a constant quantity called viscosity. Whenever fluids behaviour is studied on this basis, they are classified in two general types (Figure II-19):

- Newtonian: whenever for these fluids a shear stress is plotted vs rate of shear at constant temperature and pressure, a straight line is obtained passing through origin. These fluids always follow this linear curve. Viscosity is a constant in case of Newtonian fluids.
- A non-Newtonian fluid is one in which the viscosity is a function of some mechanical variables like shear stress or time.

There are different types of non-Newtonian fluids based upon the variation from linear behaviour (Figure II-19):

- Bingham (ideal plastic): samples with yield point (also called yield stress or yield value) only begin to flow when the external forces acting on the material are larger than the internal structural forces. Below the yield point, the material shows elastic behaviour, i.e. it behaves like a rigid solid that under load displays only a very small degree of deformation that does not remain after removing the load.
- Shear-thinning fluids (pseudoplastic): they exhibit a reduction of viscosity with increasing shear rate in steady flow.
- Shear-thickening fluids (dilatant): they exhibit an increase of viscosity with increasing shear rate.

The non-Newtonian fluids that change over time are said to have memory. Those with a time-dependent viscosity (memory materials) and those with a time-independent viscosity (non-memory materials).

A gradual decrease of the viscosity under shear stress followed by a gradual recovery of structure when the stress is removed is called “thixotropy”. The opposite type of behaviour, involving a gradual increase in viscosity under stress followed by recovery, is called “rheopexy”, “negative thixotropy” or “anti-thixotropy” [VIKA05].

Since the 1970s, the study of fresh concrete rheology has advanced significantly. Rheology involves measuring yield stress and plastic viscosity. Yield stress represents the stress necessary to initiate (static yield stress) or maintain flow (dynamic yield stress) whereas plastic viscosity expresses the increase in shear stress with increasing shear rate once the yield stress has been exceeded.

The rheology of concrete tends to be well described by the Bingham model which states that the relation between shear stress and shear rate is linear, once a yield stress has been passed (Eq. 1). The slope is referred to as the plastic viscosity (μ) and the positive intercept as the yield stress (τ_0).

$$\tau = \tau_0 + \mu \cdot \dot{\gamma} \tag{1}$$

However, materials that show a pseudoplastic or dilatant behaviour above the yield stress are better described by other methods, as the Herschel-Buckley model (Eq. 2).

$$\tau = \tau_0 + a \cdot \dot{\gamma}^b \tag{2}$$

Being *a* and *b* constants.

This model has been used for the behaviour of some specific concretes, as some self-compacting concretes in which the Bingham equation would provide a negative yield stress.

Numerous test methods are available for measuring workability [WALL11, LASK11, ROUS06b, PETI07, KHAY03, BANF03]. Most of these methods are empirical, that is, they simulate a typical placement condition and measure a value (such as a distance or time) that represents an aspect of workability. Results of empirical tests cannot be directly compared and it is necessary to use different empirical tests to characterize different aspects of workability. In contrast, the objective of using rheology measurements is to provide scientific parameters that are comparable even when measured with devices of different designs and that are capable of describing multiple aspects of workability [KOEH09].

Therefore, as workability of a fresh concrete mix is closely related to its flow properties (its rheology), a sufficient description of such flow properties requires a minimum of two parameters: the yield stress and the plastic viscosity. In general, workability tests for concrete should estimate both parameters. The yield stress and the plastic viscosity describe two physical properties of concrete and they should be considered separately. Two concrete mixes could have the same yield stress but different plastic viscosity or the same plastic viscosity but different yield stress (Figure II-20).

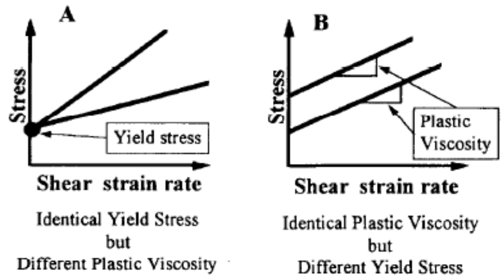


Figure II-20. Yield stress and plastic viscosity of fresh concrete [FERR98]

The flow curves (Figure II-19) represent steady-state behaviour. However, rheological measurements are highly dependent on the shear history of a sample. This time dependence is due to thixotropy, which is defined as the reversible, time-dependent decrease in viscosity at a given shear rate. When a thixotropic material is at rest, a three-dimensional network structure develops over time. The application of shear causes a breakdown of this network structure and a reorientation or deformation of particles or flocs, resulting in a reduction in viscosity at a constant shear rate or shear stress. After shear is applied for sufficient time, the material reaches an equilibrium condition where the viscosity is at a minimum for the given shear rate or shear stress.

When the application of shear is stopped, the three-dimensional network structure reforms and the original viscosity is eventually restored [KOEH09].

4.1.2 Factors affecting concrete rheology

Concrete rheology is a function of the aggregates, paste volume, and paste rheology. Paste volume depends primarily on the aggregate characteristics and paste composition depends on the aggregate characteristics and paste volume (Figure II-21).

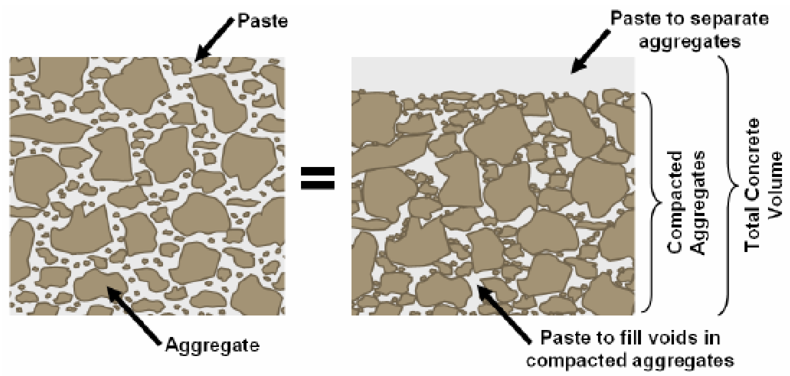


Figure II-21. Representation of aggregate in cement paste [KOEH07]

Many factors affecting concrete rheology can be explained with several models developed to relate properties of suspensions to viscosity [ROUS10].

The basis of viscosity prediction comes from Einstein's equation (Eq. 3), which suitable applies to dilute suspensions of spheres, but considerable underestimates for suspensions of practical significance.

$$\mu = \mu_s \cdot (1 + 2.5 \cdot \emptyset) \quad (3)$$

Where:

μ is the viscosity of the suspension

μ_s is the viscosity of the solvent

$\emptyset$ is the solids volume concentration

Other equations have been used and one that provides satisfactory results, although requiring the use of a new parameter, the maximum packing fraction, $\emptyset_{max}$, is the Krieger-Dougherty equation:

$$\mu = \mu_s \cdot \left(1 - \frac{\emptyset}{\emptyset_{max}}\right)^{-[\mu]\cdot\emptyset_{max}} \quad (4)$$

Where:

μ is the viscosity of the suspension

μ_s is the viscosity of the solvent

$[\mu]$ is referred to as the intrinsic viscosity of the aggregates

$\emptyset_{max}$ is the maximum packing fraction

$\emptyset$ is the solids volume concentration

The maximum packing fraction is defined as the concentration at which viscosity approaches infinity as there is contact between the solids in three dimensions throughout the suspensions. Intrinsic viscosity is a dimensionless number defined as the limiting value of the reduced viscosity as solids volume concentration approaches zero.

Fresh concrete rheology (expressed with the parameters yield stress and plastic viscosity) is affected by any possible change of its constituent materials properties, both in terms of any physical or chemical variations [PUER14], but also in terms of relative proportions of the mixture. Environmental factors such as temperature do also influence the rheology of cementitious materials (Figure II-22) [WALL11, PACI15].

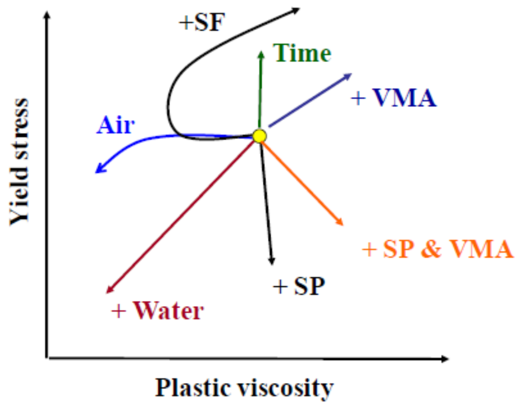


Figure II-22. Effect of different factors on rheological parameters [BILL12, WALL11]

Note: SP (superplasticiser); SF (silica fume); VMA (viscosity modifying admixture)

It is obvious that water content has a significant effect on flow and by adding water to a mixture, both yield stress and viscosity decrease since increasing the water amount dilutes the particle system and the particle concentration decreases [BILL12].

For a fixed water to cement ratio, increasing cement content (relative to total aggregate volume) increases the amount of paste surrounding aggregate particles (mortar and concrete phases) and lowers both yield stress and plastic viscosity of the mixture. In addition, cement composition and fineness can influence flow, due to differences in water demand [ERDO05].

For the case of supplementary cementitious materials, the kind of materials most often mentioned in this context are silica fume, fly ash, ground granulated blast furnace slag and limestone powder [KOEH04]. In general, by just adding powder to cement leads to increased water demand and the same response as from adding viscosity modifying admixtures will occur. But when powders are used to replace part of the cement, which is keeping the water to powder ratio constant, the response depends on the combined grading curve, or in other words, packing ability of the particles in the paste phase. Beside the packing ability, the particle shape of the powders play a very important role, and this is often reported for silica fume and fly ash [BILL12].

Admixtures also influence paste and concrete flow significantly [PUER14, HU05]. By dispersing the particle system with a water reducer or a superplasticizer, the flocks of aggregated particles are broken up. The system, however, is not diluted by doing this, and therefore, the main effect of adding these kind of dispersing admixtures is a reduced yield stress and a more or less unaffected viscosity [BANF11].

The general function of viscosity modifying admixtures is to bind water which leads to an effect opposite to that when water is added. This also goes for the case when filler or powder materials are added, that is, binding water. Air entraining admixtures generally decrease the viscosity due to the small bubbles acting like ball bearings, reducing the friction during shearing, and also because the air content increases the paste volume [BANF06]. However, air entraining admixtures can also increase the yield stress of the paste phase since the negatively charged small bubbles can cause bridging between hydrating cement particles. However, the decrease of viscosity in the concrete scale dominates over any change of yield stress in the paste scale.

Contrary to increasing cement content, increasing aggregate content (relative to a fixed water to cement ratio) increases viscosity, due to increased particle interactions [ERDO05]. The particle size distribution of aggregates significantly influences workability and rheological properties. It is generally accepted that a well graded aggregate with particles of a wide range of sizes decreases viscosity. Increasing the packing density generally improves the flow. The morphological properties of aggregates also influence the rheology of concrete [QUIR03]. Spherical shapes or rounded aggregates give lower viscosity than angular ones. Rounded and smooth aggregates require less water than angular or flat and/or elongated particles to achieve the same slump. Spherical particles flow more easily around each other and result in reduced viscosity. Size distribution and particle shape can be especially important in the case of the microfines of aggregates. Although these increase the water demand of the mixture due to increased surface area, it has been reported that they can improve flow by improving the grading of the fine aggregates.

Table II-3 summarizes the factors influencing concrete rheology. In general terms, angular and poorly shaped aggregates increase yield stress and plastic viscosity. Increasing the paste volume reduces yield stress and plastic viscosity. If the aggregates and paste volume are held constant, changes in paste rheology are generally matched in concrete rheology (e.g. increasing paste yield stress and viscosity increases concrete yield stress and viscosity).

Table II-3. Factors influencing concrete rheology [KOEH04]

	Yield stress	Plastic viscosity
Aggregates		
Aggregate volume fraction	Increase	Increase
Sand-aggregate volume	Optimum value	Optimum value
Shape	Round or cubical preferred to flat, elongated or angular	
Texture	Smooth preferred to rough. Increase for high and/or very high aggregate volume concentration	
Gradation	Uniform gradation, high packing density preferred	
Microfines content	Mixed	Mixed
Water content	Decrease	Decrease
Cement content	Decrease	Decrease
Supplementary cementitious materials		
Fly ash	Decrease	Mixed
Silica fume (low dosage)	Decrease	Decrease
Silica fume (high dosage)	Increase	Increase
Ground granulated blast furnace slag	Mixed	Increase
Admixtures		
Water-reducing admixture	Decrease	Mixed
Air-entrainment agent	Mixed	Decrease
Viscosity-modifying admixture	Increase	Increase

4.1.3 Robustness

Robustness of concrete is defined as the capacity of the material to tolerate certain variations in material characteristics and mixture parameters. A robust concrete (mix B in Figure II-23) has lower sensitivity to such variations than a non-robust concrete (mix B in Figure II-23).

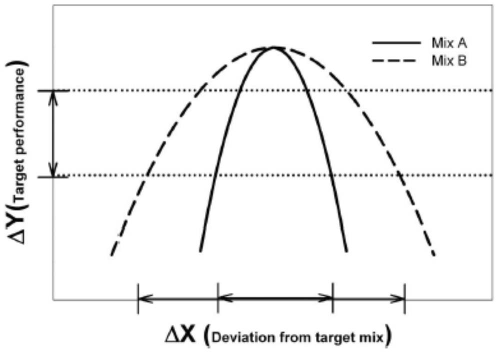


Figure II-23. Comparison of two mixes in terms of robustness [NUNE13]

The increase of concrete robustness can be achieved in two different ways. One possible way is to reduce the range of the interval ΔX, i.e. reducing the deviations from the target mix (Figure II-23). This can be accomplished by reducing variations in the constituent materials through more quality control or by increasing the accuracy of existing equipment. Another way to increase robustness is to change from a mix A to one a mix B (Figure II-23), that is, mix B allows for larger deviations ΔX while maintaining the properties inside the acceptance interval, represented by ΔY. This can be achieved by a well-balanced selection and proportioning of constituent materials or by changing the constituent materials [NUNE13].

One of the main obstacles to a wider use of self-compacting concrete is its sensitivity to small variations of the constituent materials, mix proportions, and other external factors, which may lead to variability of performance [ASGH16, BONE07].

According to “The European Guidelines for Self-Compacting Concrete”, robustness is an important step in the SCC design process. Most constituent variability can be associated with a change in water requirement, either due to changes in moisture content of materials or changes in grading / specific surface (Figure II-24). A well-designed and robust SCC should tolerate a change in water content of up to 5 to 10 L/m^3 without falling outside the specified class of performance [EFNARC05].

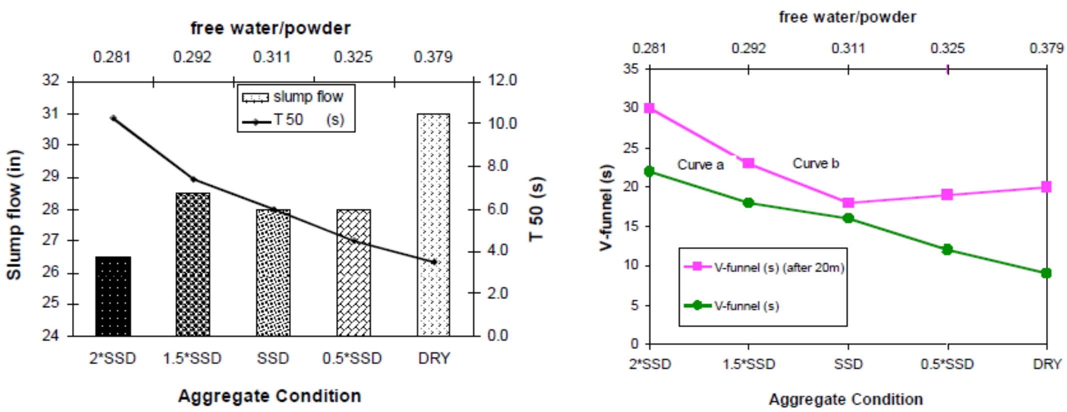


Figure II-24. Slump flow and V-funnel tests for variations in moisture content of aggregates [BONE07]

Nunes et al. [NUNE06] proposed to assess the robustness of SCC in terms of the frequency of satisfying the acceptance criteria despite daily fluctuations of the ingredients. These authors observed that the water to powder volume ratio exhibited the greatest effect on SCC properties, and the superplasticiser to powder weight ratio and solid volume also influenced them significantly.

Higher paste volume may improve robustness by reducing the required yield stress and viscosity of cement paste to maintain the same concrete slump flow [SHEN14]. Kwan and Ng [KWAN10] concluded that the robustness of SCC can be improved by increasing the powder content. The incorporation of cementitious materials of high specific gravity, such as slag, dolomite, or limestone, increases robustness [RIGU09]. Higher robustness is also achieved by increasing the viscosity of the mixture by means of material selection and incorporation of a viscosity modifying admixture [GETT09]. The use of a viscosity-enhancing admixture can increase SCC stability when changes in sand humidity occur [NAJI11]. Higher fine aggregate to coarse aggregate ratio also improves robustness [SHEN14]. Although smaller aggregate size, better gradation, and higher aggregate packing density can all improve robustness of SCC mixes, smaller aggregate size and better gradation seem to have a more significant impact on robustness than higher aggregate packing density.

4.1.4 Thixotropy

Linking to the rheological characteristics that influence the capacity to deform in a homogeneous way (fresh properties), the structural build-up of static yield stress and plastic viscosity after a period of rest is a very important issue for a self-compacting concrete. This phenomenon called thixotropy is defined as the reversible, isothermal, time-dependent decrease in viscosity when a fluid is subjected to increased shear stress or shear rate (Figure II-25).

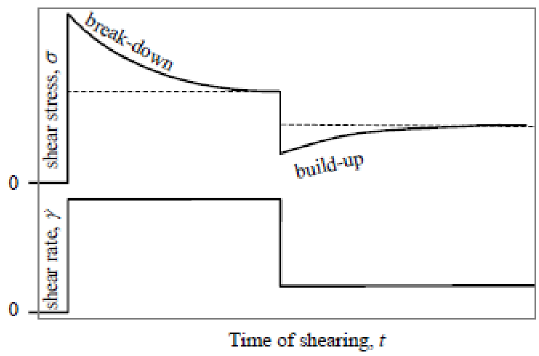


Figure II-25. Manifestation of thixotropy in concrete rheology measurement [KOEH09]

Figure II-26 shows a simple physical explanation of the thixotropic behaviour. As shown in Figure II-26 (a), the particle interaction forces (colloidal interactions in the case of cement pastes) determine for each particle an equilibrium position for which the potential energy is minimum. As long as the energy ΔE given to the system is lower than a given value, the particle does not leave this position (Figure II-26 (b)). When the applied stress or strain stops, the particle comes back to its initial position (elastic solid behaviour). However, if the external energy is larger than a certain value, the particle is then able to leave this potential energy well, as shown in Figure II-26 (c), and the flow initiates (yield stress behaviour). In the case of systems displaying thixotropic behaviour, the depth of the potential energy well increases at rest with time because of Brownian motion and a possible evolution of the colloidal interactions. As shown in Figure II-26 (d), the needed energy ΔE' for the particle to leave the well increases (increase of the apparent yield stress). However, if the particle leaves the well, the well comes back to its initial depth [ROUS06a].

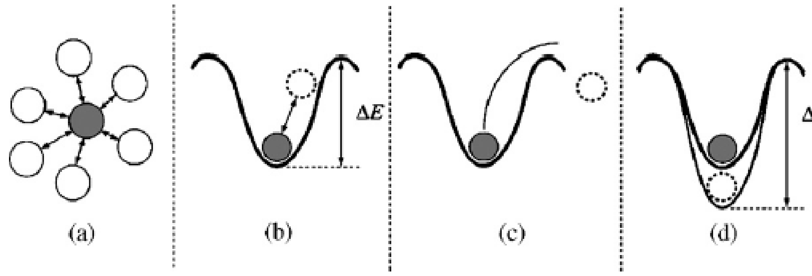


Figure II-26. A physical explanation of the thixotropic behaviour of cementitious materials [ROUS06a]

Figure II-27 gives another description of thixotropic behaviour of cementitious materials. These can be considered as solid-dispersion systems in which physical interactions between various molecules can be high after a certain period of rest, leading to the formation of a gel structure that is highly cohesive despite its high water content. Bond among various molecules leading to a rise in cohesiveness can correspond to hydrogen or ionic bonding [KHAY02]. Such bond takes place especially at a low shear rate and can be destroyed by mixing the dispersion at a high shear rate (Figure II-27). The reagglomeration and reestablishment of the various bonds among adjacent molecules can be established again following a rest period.

A fast build-up of viscosity can be due to a thixotropy whereby the cohesiveness increases with the elapsed time of rest. This can be due to physical effects, chemical effects, or both, associated with cement hydration. The physical explanation relates to a build-up of interparticle friction and cohesion among the various cement particles and admixture molecules.

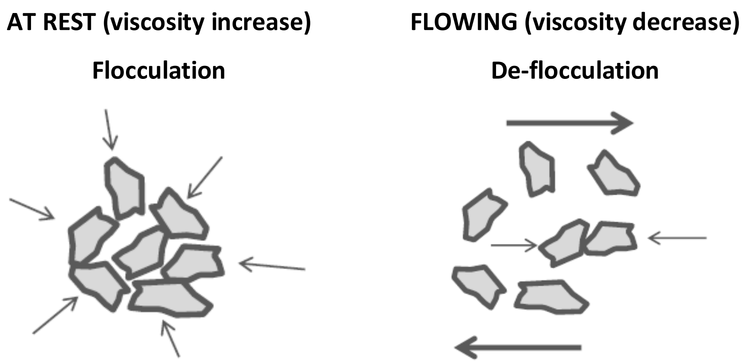


Figure II-27. Visualization of the thixotropic behaviour of cementitious materials

The explanations of flocculation mechanism include two aspects: the first one is attractive forces and the second one is repulsive forces. Although the cement paste cannot be totally defined as a colloid, it is true that the cement paste consists of colloid particles. The particles of cement paste have charged particles surface. These charges are intrinsic and come from interactions during dissolution, adsorption and ionization of particles. Besides, the Van der Waals force can be characterized as a secondary bond. It exists between molecules and is much weaker than the primary bonds. If the molecules are contacting close to each other, the secondary forces will be very effective [QUAN10].

Secondary bonds can also be defined as physical bonds. It is possible that these weaker secondary forces are the main factors of the thixotropic properties of cement paste. In this sense, they are the main reasons why cement paste has the reversible flocculation and deflocculation when it is placed. There are three types of weaker secondary forces: London dispersion forces (Van der Waals), dipole-dipole interactions and hydrogen bonds. The former is the most important factor to determine the flocculation of cement paste (Table II-4).

The cement paste is made of heterogeneous materials and it has different phases because of hydration, therefore, more electrostatic attraction will also be created between particles. The major factors affecting the flocculation of cement paste involve distribution of particle size, volume fraction of particles, interparticle forces and cement hydration. It is stated that Van der Waals forces, electrostatic forces and hydration forces cause the rheological behaviour of cement paste [FLAT04, ROUS10, QUAN10].

Table II-4. Strength of secondary bonds

Bond type	Energy of dissociation (kcal)
Hydrogen bonds	12 ~ 16
Dipole-dipole interactions	0.5 ~ 2
London dispersion forces (Van der Waals)	Smaller than 1

In practice, a “thixotropic concrete” can be defined as a concrete displaying a rather short flocculation characteristic time (typically several minutes) and a de-flocculation characteristic time of several tens of seconds in the 1 to 10 s^{-1} shear rate range [ROUS06a].

Thixotropy can be assessed by determining the difference between the ascending and descending legs of the shear stress – shear rate rheograms (Figure II-28). Such hysteresis represents a quantitative measurement of the energy necessary to disturb the structure of a given volume of concrete following some period of rest.

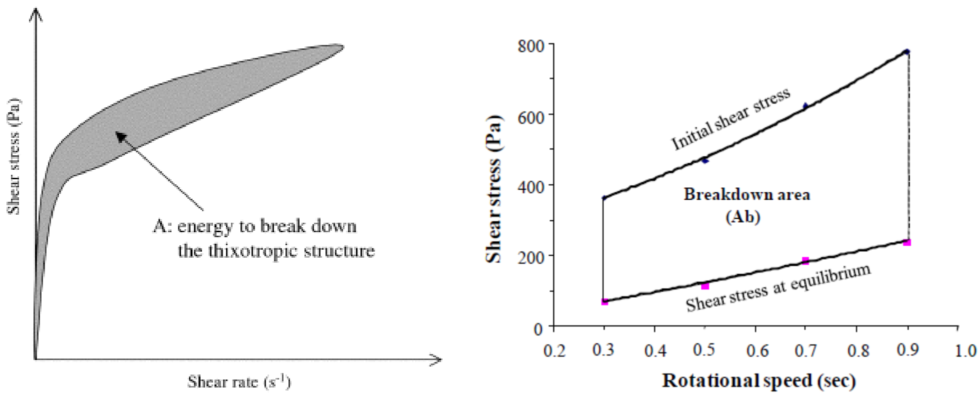


Figure II-28. Measurements of thixotropy [KHAY02, KHAY12a]

Finally, thixotropy contributes to increase segregation resistance and to reduce formwork pressures. However, too much thixotropy reduces placeability. The ideal mixture proportions for fluid concrete are located somewhere between two opposite objectives. The concrete has to be as fluid as possible to ensure that it will fill the formwork under its own weight, but it has to be stable enough to withstand the high strain rates generated by flow in a confined zone. Therefore, a compromise between stability and fluidity has to be reached. The most straightforward approach is to find the minimum fluidity (or workability) that will guarantee adequate filling of the formwork and assume that this minimum fluidity will ensure the maximum acceptable stability [ROUS09].

4.1.5 Concrete rheometers

Empirical tests for fresh concrete have been developed almost continuously from the 1920s up to the present day, but development of rigorous definition is needed and, therefore, rheometers have been designed specifically for the measurement of concrete. Early experiments measured the drag or torque exerted on a body immersed in the concrete. From the 1970s, measurements with coaxial cylinders, parallel plates or impeller had been made and some theoretical understanding achieved (Figure II-29).

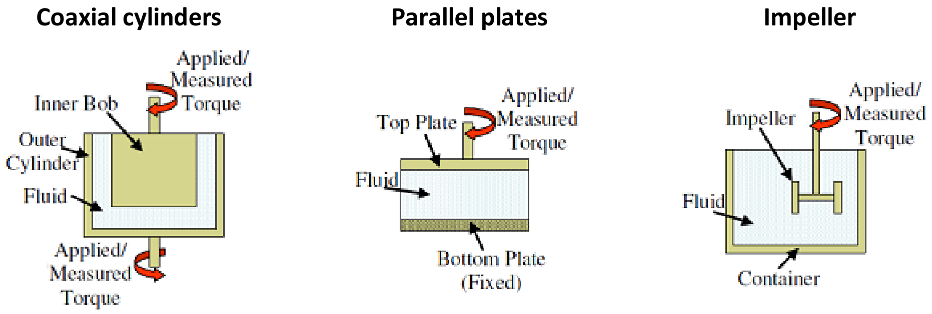


Figure II-29. Typical rheometer geometry configurations [KOEH09]

The characterization of concrete rheology is complicated due to the presence of large aggregates. The size of the sheared specimen in a rheometer must be sufficiently large relative to the aggregate size in order to obtain a representative measurement of the bulk material [KOEH09]. The design of a rheometer for concrete allowing measurements of a flow curve describing the relationship between shear stress and shear rate is taken from the science of fluid rheology. Rheometers may be shear stress controlled or shear rate controlled, although most rheometers for concrete are shear rate controlled.

A coaxial rheometer is composed of two concentric cylinders. The outer cylinder is usually stationary and the inner cylinder rotates at a controlled speed. The shear stresses generated by the fluid are measured on the inner cylinder. To be able to compute the shear stress and shear rates as well as calculate the yield stress and plastic viscosity according to the Bingham equation, the gap between the cylinders needs to be relatively small as compared to their diameters [FERR01].

For concrete, the gap needs to be at least three to five times the size of the coarse aggregate to avoid interaction between the aggregates and the walls of the rheometer. These dimensions would have to be increased with the maximum size of the aggregate, rendering this type of instrument unsuitable for field use because it would not be easily transportable outside the laboratory.

Because of the impracticability of using a coaxial cylinders viscometer of anything like ideal dimensions for fresh concrete, Tattersall and co-workers developed a highly successful and practical apparatus in which an interrupted helical impeller rotates in a cylindrical bowl of fresh concrete [BANF06, TATT83]. This was also referred to as the “Two-Point” rheometer.

The torque on the rotating impeller is determined by measuring the pressure in the hydraulic drive unit at a range of speeds. Assuming that the mean effective shear rate is proportional to the speed of rotation of the impeller and that shear stress is proportional to torque, the flow curve can be drawn [BANF11]. This method does not allow for the calculation of viscosity and yield stress in fundamental units, but it enables the study of concrete flow under various shear rates. The “Two-Point” apparatus was modified and computerized by Wallevik and Gjørv [WALL88].

Other approaches to the measurement of fresh concrete rheology have been the BML and CEMAGREF-IMG coaxial cylinders rheometers, the BTRHEOM rheometer using parallel plates, and the IBB and ICAR rheometers using an impeller [LARR95, BEAU94, KOEH04].

In the BML and CEMAGREF-IMG devices, one cylinder (inner cylinder for the CEMAGREF-IMG and outer for the BML) is rotated at varying speed (Figure II-30). Torque on the inner cylinder is measured when a concrete sample fills the gap between the inner and outer cylinders. The most striking difference between these two rheometers is the size of test sample. For BML, the concrete sample size is only 17 litres, but the CEMAGREFIMG tests with 500 litres [FERR03].

CEMAGREF-IMG **BTRHEOM**

Figure II-30. Concrete rheometers: CEMAGREF-IMG (left) and BTRHEOM (right)

The BTRHEOM rheometer is a parallel plate device (Figure II-30). The concrete sample is placed within a cylindrical container having a fixed bottom plate. A top plate embedded in the concrete rotates at varying speeds and the torque on this plate is measured [FERR03].

The IBB, Two-Point and ICAR rheometers have a rotating impeller inserted into fresh concrete placed in a cylindrical container (Figure II-31). The IBB uses an H-shaped impeller, whereas that for the Two-Point has a helical pattern. The ICAR includes a four-bladed vane [KOEH06]. These impellers rotate axially at the centre of the sample chamber, and the torque generated is measured as a function of rotation rate.

Tattersall Two-Point **IBB** **ICAR**

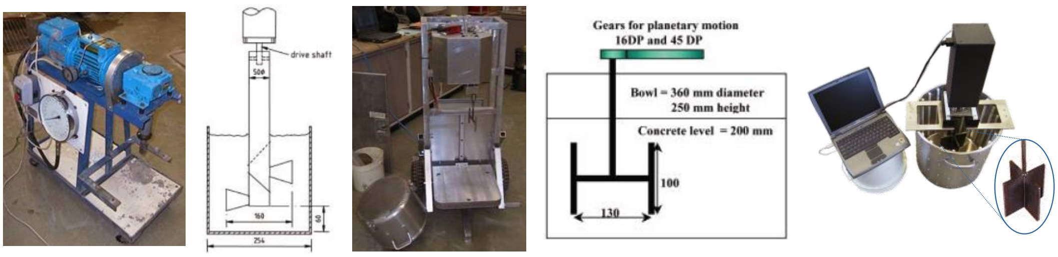


Figure II-31. Concrete rheometers: Two-Point (left), IBB (centre) and ICAR (right)

Although a correlation exists among the different rheometers, the absolute values calculated for a given mixture are not identical. It was found that all rheometers rank mixtures in the same order both for yield stress and for plastic viscosity to a good degree of statistical confidence [FERR03]. Differences in absolute values were attributed to several causes, such as slip at the instrument wall interface with concrete or the confinement of concrete between moving parts of the rheometers.

4.2 Materials

The constituent materials for SCC are the same as those used in traditional vibrated concrete [EFNARC02]. In most cases the requirements for constituents are individually covered by specific European standards. However, in order to be sure of uniform and consistent performance for SCC, additional care is needed in initial selection and also in the continual monitoring for uniformity of incoming batches.

Aggregates

The same aggregates are used to make SCC and conventional concretes. To increase segregation resistance and keep cohesion, a large amount of fine aggregates is required. The maximum size of the aggregates depends on the particular application and is usually limited to 20 mm. Particles smaller than 0.125 mm contribute to the powder content. The moisture content should be closely monitored and must be taken into account in order to produce SCC of constant quality.

Cement, additions and admixtures

All cements which conform to EN 197-1 [EN197-1] can be used for the production of SCC. The correct choice of cement type is normally dictated by the specific requirements of each application or what is currently being used by the producer rather than the specific requirements of SCC.

Given the high powder contents required to achieve SCC workability, it is often necessary to include supplementary cementitious materials or mineral fillers as part of the powder. The powder content must contain a minimum amount of cement for strength and durability. Supplementary cementitious materials can be used to improve workability and durability [PUER14], reduce heat of hydration, and reduce cost [DEEB13]. Mineral fillers significantly finer than cement typically enhance workability and may contribute to accelerated strength gain. Mineral fillers approximately the same size of cement typically have minimal effects on workability and do not contribute to strength [QUIR03].

The requirements for superplasticisers in SCC are: high dispersing effect for low water to powder (cement) ratio, maintenance of the dispersing effect for at least two hours after mixing, and less sensitivity to temperature changes [OKAM03].

Superplasticisers or high range water reducing admixtures are an essential component of SCC. The polycarboxylate based high-range water reducer disperse the cement particles by its steric hindrance effect induced by long grafted side-chain, thus reducing the loss of water due to entrapping in cement flocks [PUER05, ALON07]. Therefore more free water was available in freshly mixed concrete to maintain high workability.

Viscosity modifying admixtures may also be used to help reduce segregation and the sensitivity of the mix due to variations in other constituents, especially to moisture content. Other admixtures including air entraining, accelerating and retarding may be used in the same way as in traditional vibrated concrete but advice should be sought from the admixture manufacturer on use and the optimum time for addition [EFNARC05].

4.3 Mix proportions

A key phase, when producing SCC, lies on the selection of constituent materials and the design of mix proportions so as to obtain adequate properties of fresh concrete. In recent years, the complexity of mixture proportioning has increased with the increasing variety of components available to produce concrete: chemical admixtures (superplasticizers, viscosity agents, etc.), mineral additions (limestone filler, fly ash, ground granulated blast furnace slag, silica fume, etc.) and several kinds of cements and aggregates (crushed, rounded, etc.). This means that a large number of variables must be considered in the mix design process and since their interactions are difficult to predict often a large number of tests must be carried out to optimize the SCC mixture [NUNE09].

As mixture design is a critical step to obtain high quality SCC, it should consider: widely applicable, strong robustness for variable raw materials, technical requirements, sustainability and cost [SHI15].

The optimal SCC design is laid on three main foundations [URBA15]: process aiming at aggregate grain size distribution and content optimisation (by blocking criterion and/or minimum voids criterion), selection of rheological parameters of filling phase (i.e. paste or mortar), and minimum paste volume estimation (using overfilling or coating methods), typically followed by admixtures content optimization.

There is no method fully meet these requirements. Based on the literature review, different SCC mixture design methods were found [SHI15]. The empirical design method is easy to follow, although intensive laboratory testing on available raw materials is needed to obtain satisfactory mix proportions. The compressive strength method presents a clear and precise procedure to obtain specific quantities of materials, takes into account the gradation of fine and coarse aggregates and the contribution of pozzolanic materials, and minimizes the need for trial mixes. However, this method requires adjustments to all ingredients to achieve an optimal mixture proportion.

The close aggregate packing method mainly considers the relationships between paste and aggregate. Hence, this method is simpler and requires a smaller amount of binders. However, SCC produced based on this method tends to segregate easily, which is a problem for construction. The method based on statistical factorial model can simplify the test protocol required to optimize a given mixture by reducing the number of trial batches to achieve a balance among mixture variables. However, establishment of statistical relationships needs intensive laboratory testing on available raw materials. Finally, the method based on rheology of paste model can reduce the laboratory work and materials, and provide the basis for quality control and further development of new mineral and chemical admixtures.

Okamura and Ozawa [OKAM03] have employed the following approaches to achieve self-compactability: limited aggregate content, low water-powder ratio and use of superplasticiser (Figure II-32). The energy required for flowing is consumed by the increased internal stress, resulting in blockage of aggregate particles. Limiting the coarse aggregate content, whose energy consumption is particularly intense, to a level lower than normal is effective in avoiding this kind of blockage.

Highly viscous paste is also required to avoid the blockage of coarse aggregate when concrete flows through obstacles. When concrete is deformed, paste with a high viscosity also prevents localized increases in internal stress due to the approach of coarse aggregate particles. High deformability can be achieved only by the employment of a superplasticiser, keeping the water to powder ratio to a very low value.

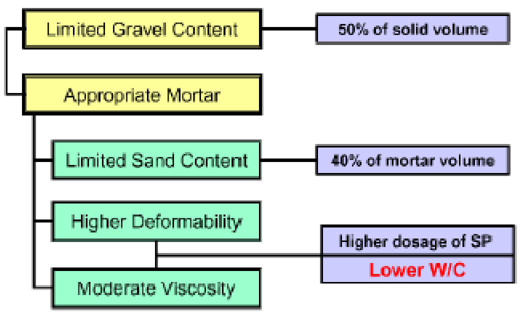


Figure II-32. Typical approaches to achieve self-compactability [OKAM03]

According to an analysis conducted by Domone [DOMO06] of 68 SCC case studies, mix proportions vary widely and there is not a unique solution for any given application. The analysis found that coarse aggregate contents varied from 28 to 38% of concrete volume, paste content varied from

30 to 42% of concrete volume, powder content ranged from 445 to 605 kg/m^3, water/powder ratio ranged from 0.26 to 0.48, and fine aggregate content varied from 38 to 54% of mortar volume. The majority of case studies used maximum coarse aggregate sizes of 16 to 20 mm. In general, all mixtures used some type of non-Portland cement powder, with limestone powder the most common addition.

Indicative typical ranges of proportions and quantities in order to obtain self-compacting concrete are given below compared to conventional vibrated concrete ones (Figure II-33):

- Lower coarse aggregate content (sand/aggregate = 0.50 vs. 0.40).
- Lower maximum size of aggregate (19 mm or lower vs. up to 37.5 mm).
- Higher paste volume (28-40% vs. 25-30%).
- Higher powder content (cement, filler and additions > 415 kg/m^3).
- Lower water to powder ratio (0.30-0.40).
- Increased high range water reducing admixture dosage.
- Use of viscosity modifying admixtures in some cases.

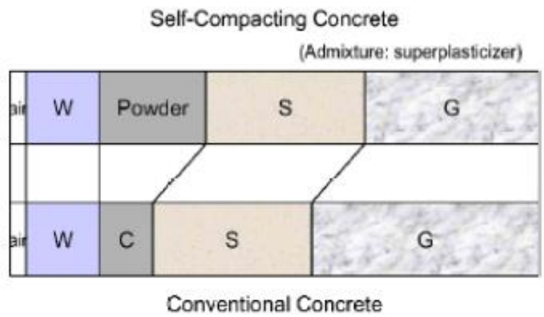


Figure II-33. Ranges of proportions SCC vs. conventional concrete [OKAM03]

4.4 Mixing procedure

What are the principal factors that influence the rheological parameters of concrete? The first factors are the composition of the concrete, including the chemical and mineral admixture dosage and type; the gradation, shape, and type of the aggregates; the water content; and the cement characteristics. The same mixture design can result in different flow properties if secondary factors are not taken into account. These are [FERR01]:

- Mixer type: pan, truck, and so on. These may induce various levels of deflocculation and air entrainment.
- Mixing sequence, that is, the sequence of introduction of the materials into the mixer.
- Mixing duration.
- Temperature.

There is no requirement for any specific mixer type. However, with SCC it is particularly important that the mixer is in a good mechanical condition and that it can ensure full and uniform mixing of the solid materials with sufficient shear action to disperse and activate the superplasticiser [EFNARC05].

Generally, due to high cementitious content, SCC typically requires longer mixing time compared to normal concrete, and it was noted that this might lead to a reduction in the capacity of the concrete plant. The mixing time necessary should be determined by practical trials. This longer mixing time is needed for securing complete structural breakdown of the SCC mixtures in order to utilize its superb flow properties [BONE07]. However, it is recognized that it is not only the mixing time the key parameter, but rather the shear energy and shear rate. In fact, for a given mixture, completely different flow curves are obtained by varying these two parameters.

Chopin et al. [CHOP04] studied the effects of mixing time on robustness. The parameters varied in their study included the quantity of powder, use of limestone filler, and various types and contents of silica fume and superplasticiser. These authors concluded that although the SCC mixtures generally require longer mixing times than conventional mixtures, their mixing time can be reduced by increasing the fine particle content (with a constant water to cement ratio), increasing the total water amount, and replacing part of the cement by silica fume.

4.5 Fresh-state properties

Properly designed SCC should have the high workability necessary for ease of placement while maintaining high stability in order to secure homogeneous distribution of in situ engineering properties and durability [KHAY08]. Unlike conventional vibrated concrete, successful design of SCC implies greater attention to some factors, including the type of nominal size of coarse aggregate, aggregate packing, binder composition and content, and water to cementitious materials ratio.

The basic workability characteristics of SCC that must be balanced to ensure successful casting of SCC include filling ability, passing ability, and resistance to segregation. These properties are affected by a number of parameters, including raw material properties and concrete proportioning.

The filling ability is defined as the ability of concrete to flow under its own mass and completely fill formwork. The filling ability of fresh SCC is closely related to that of the cement paste. An increase in water to cementitious materials ratio, or water to binder ratio, can secure high filling ability. However, it can also reduce the cohesiveness of the paste and mortar, thus leading to segregation of fine and coarse aggregate particles [KOEH07].

Another parameter that affects filling ability is the interparticle friction between the various solid particles in the concrete matrix. Concrete must have adequate paste volume and paste rheology for the given combined aggregate. Sufficient paste volume ensures that voids between aggregates are filled and that sufficient spacing is provided between aggregates (Figure II-34). If the concrete contains insufficient paste volume, the paste will not convey the aggregates regardless of the rheology of the paste. The use of high-range water reducing admixture can disperse cement grains and reduce interparticle friction among cement particles. It is also essential to reduce the relative volume of coarse aggregate and sand, and increase the paste volume in order to enhance filling ability.

Figure II-34. Excess paste layer around aggregates [DEEB13]

Filling ability should be tested with the slump flow test (EN 12350-8) [EN12350-8], including measurements of the horizontal flow diameter (SF), time to spread 500 mm (t500) and visual stability index (VSI). This test is the reference empirical test for evaluating the deformability of SCC without obstructions [ROUS06b].

The passing ability is the ability of concrete to flow through confined conditions, such as the narrow openings between reinforcing bars. The passing ability of fresh SCC is primarily affected by the aggregate characteristics and the paste volume [KOEH07]. Reducing the maximum aggregate size and coarseness of an aggregate grading and improving the aggregate shape and angularity result in increased passing ability. Increasing the paste volume reduces the volume of aggregates and reduces the interparticle friction between aggregates.

Passing ability is often measured with the L-box and J-Ring tests (EN 12350-10 and EN 12350-12) [EN12350-10, EN12350-12].

The segregation resistance is the ability of concrete to remain uniform in terms of composition during placement and until setting. This property encompasses both static and dynamic stability.

Static stability is affected by the relative densities of the aggregate and paste, the rheology of the paste with time, the aggregate shape and grading, and the characteristics of the element (such as width and spacing of reinforcement). Changing the paste rheology is generally the most productive means of improving static stability. An SCC mix with an aggregate that is well-graded for segregation resistance can exhibit severe segregation if the paste rheology is improper. Improving the aggregate grading is also effective for reducing segregation resistance [KOEH07].

Dynamic stability is mainly affected by the cohesiveness and passing ability of the concrete. Static stability should be measured with the column segregation test while dynamic stability is usually measured indirectly with measurements of filling and passing ability.

The sieve segregation test is widely used to measure the segregation resistance (EN 12350-11) [EN12350-11].

The fresh-state properties are measured by means of several specific empirical tests (Figure II-35) [EFNARC05]. However, no single test has been found to fully characterize the three basic workability characteristics of SCC.

Figure II-35. Empirical tests: slump flow, L-box, V-funnel, J-Ring

Rheology can be used to characterize concrete flow characteristics and to optimize mixes for filling ability, passing ability, and segregation resistance. From a rheological point of view, SCC is characterized by low yield stress to ensure high deformability (Figure II-36). It should be near zero to ensure concrete flows under its own mass. Moreover, SCC is characterized by moderate plastic viscosity to maintain homogeneous suspension of solids. It should not be too low, which would result in a lack of stability, or too high, which would result in sticky and cohesive mixes that are difficult to pump and place.

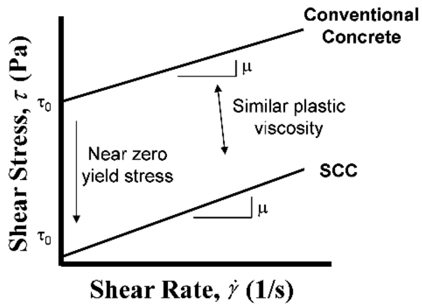


Figure II-36. Yield stress and plastic viscosity (SCC and conventional concrete)

To increase filling ability and passing ability, the yield stress and plastic viscosity should be reduced. If the yield stress and plastic viscosity are too low, however, the concrete may become unstable, resulting in reduced filling and passing abilities. To increase segregation resistance, the yield stress and plastic viscosity should generally be increased.

On the other hand, self-compacting concrete might be less robust than ordinary concrete due to a combination of detailed requirements, more complex mix design, and inherent low yield stress and plastic viscosity.

Thus, SCC is usually more susceptible to small changes in raw materials characteristics and mixing conditions than conventional vibrated concrete. For example, variations in cement or fines content, batching water, water to powder ratio, or high-range water-reducing admixture dosage can greatly affect rheological properties and workability of SCC [NUNE06, RIGU09, NAJI11].

Sand moisture content and superplasticiser dosage are considered as major parameters affecting robustness of SCC [KHAY12b]. In terms of workability characteristics, the slump flow and J-Ring tests are found to be sensitive for robustness evaluation [GETT09].

The production and performance of self-compacting concretes can be managed with the quality control of raw materials and with the rheological parameters control using workability boxes. A workability box defines an area of combinations of yield stress (typically related to the diameter of slump flow test) and plastic viscosity (typically related to the times of slump flow test and V-funnel test) (Figure II-37). If the test values are inside this area, then the SCC mix is ensured to show proper flowability and stability.

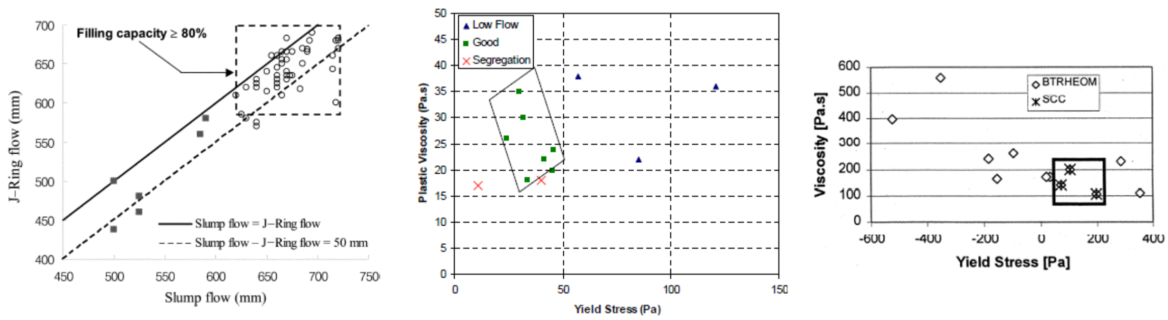


Figure II-37. Examples of workability boxes [HWAN06, KOEH09, FERR00]

Finally, regarding thixotropy, as SCC should be as fluid as possible but not too much in order to obtain a stable self-compacting material, there also exists an optimum thixotropic behaviour for a given concrete, casting process and element to be cast [ROUS08]. It was shown that stability of SCC can be improved when the constitutive cement paste is highly thixotropic. It was also demonstrated that formwork pressure strongly decreases for highly thixotropic SCC.

The relationship between the degree of thixotropy and lateral pressure variations shows that the higher the degree of thixotropy is, the less the concrete develops pressure right after filling the formwork [ASSA04]. This tendency becomes more pronounced after 100 and 200 min from casting. This enabled then the establishment of various models to predict the pressure resulting from a given concrete composition through the evaluation of the rheological characteristics.

However, highly thixotropic SCC may induce, in specific conditions, distinct-layer casting of the material that can generate lowered mechanical resistances in the final structure [ROUS08]. Moreover, a weak interface between layers may locally increase porosity and permeability to aggressive substances.

4.6 Hardened-state properties

In view of the range of materials, mix designs and test procedures used, the existence of some scatter in hardened mechanical properties of self-compacting concrete when analysing data from different studies is understandable [DOMO07].

At similar water to cement ratios the characteristic strength of SCC is at least equal to that of conventional concrete, and has a similar strength development for the same grade. Due to the low water to cement ratio used in SCC the compressive strength will generally be above 40 MPa and can be up to 100 MPa. It was found that the difference of strength between mixes with crushed and uncrushed coarse aggregate is lower for SCC than for normally vibrated concrete [DOMO07]. Limestone powder, a commonly used addition in SCC, contributes significantly to strength at ages up to at least 28 days. The ratio of cylinder to cube strength for SCC varies from about 0.8 at strengths of 30 MPa to near 1 at strengths of 90 MPa.

The splitting tensile strength is also comparable to the same grade of conventional concrete. The ratio of tensile to compressive strength for SCC is similar to that for normally vibrated concrete, with the great majority of cylinder splitting results for both types of concrete falling in the upper half of the range suggested in Eurocode (Figure II-38).

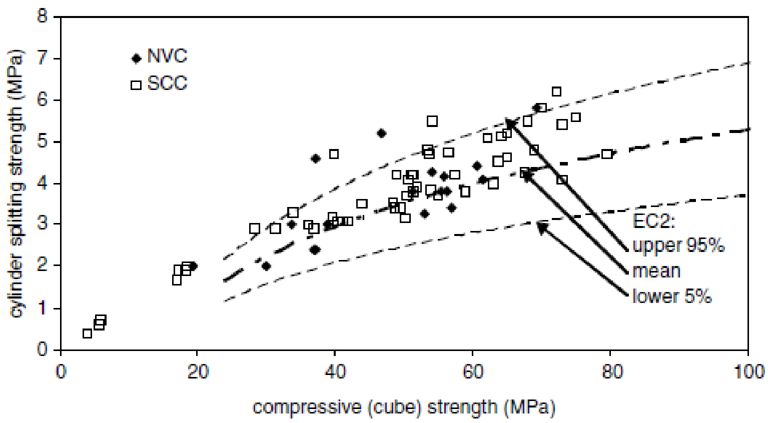


Figure II-38. Splitting tensile strength vs. Compressive strength [DOMO07]

Because of the relatively low water to cementitious materials ratio typically used in proportioning SCC and the incorporation of supplementary cementitious materials, SCC could develop higher flexural strength and flexural to compressive ratio than conventional slump concrete [KHAY08].

The modulus of elasticity of SCC can be up 40% lower than of normally vibrated concrete at low compressive strength (20 MPa), but the difference reduces to less than 5% at high strengths (90–100 MPa) (Figure II-39).

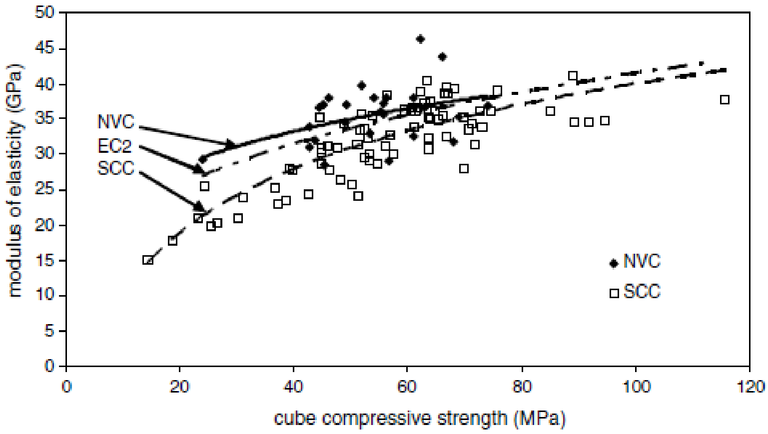


Figure II-39. Modulus of elasticity vs. Compressive strength [DOMO07]

Tests performed on creep and shrinkage of different types of SCC show that: the deformation caused by shrinkage may be higher, the deformation caused by creep may be lower, and the value for the sum of the deformations due to shrinkage and creep are almost similar.

As concrete compressive strength is related to the water to cement ratio, in SCC with a low water to cement ratio drying shrinkage reduces and the autogenous shrinkage can exceed it. Due to the higher volume of cement paste, the creep coefficient for SCC may be expected to be higher than for normal concrete of equal strength.

Finally, the bond strength of SCC to embedded reinforcing and prestressing steel, either in the relation to concrete strength or in the top-bar effect in deep sections, is essentially similar to the equivalent normally vibrated concrete.

4.7 Durability

As some general and practical conclusion, it can be mentioned that the durability of SCC is at least as good as the durability of traditional concrete with similar water to cement ratio and cement content.

As long as the self-compacting properties are verified on site, a less variable and denser concrete is achieved. It could also be said that the compaction, and therefore durability, of the concrete is more guaranteed with the use of SCC as it reduces the potential for human error (in the form of poor compaction). The high fines content and the need for well-graded aggregates also improve the concrete, producing a more dense interfacial transition zone between the aggregate and the cement matrix. All these effects are beneficial for durability, although because of its relatively recent use, knowledge of SCC long-term durability is still restricted.

A denser microstructure can decrease diffusion of chloride ions and other harmful substances, increase frost resistance, and improve service life of the structure. Densification of the cement matrix and increase in concrete cover, in well-cured and uncracked concrete can reduce the risk of corrosion. At similar compressive strength, SCC can develop significantly lower permeability coefficient, water sorptivity, and water absorption compared to conventional vibrated concrete [KHAY08].

5 SELF-COMPACTING RECYCLED CONCRETE (SCRC)

Self-compacting recycled concrete (SCRC) is a further step towards a tailor-made environmentally friendly concrete. This new technology links characteristics and performance of both recycled and self-compacting concretes (Figure II-40) and it has been recently developed for the last decade. However, SCRC has not been suitably researched yet and limited studies have been conducted on the use of recycled aggregates and their influence on self-compacting concrete behaviour.

Figure II-40. The origin of self-compacting recycled concrete

5.1 Materials

The materials used to produce SCRC are the same as in SCC, but for recycled aggregates as replacement of natural aggregates. The type and shape of coarse aggregate, combined gradation of sand and coarse aggregate, content of cement and supplementary cementitious materials, paste volume, and water to powder ratio have to be considered when designing SCRC as in SCC.

Aggregates

As fine aggregate, typical natural sands from riversides or resulting from the process of crushing rock are used. Shape and texture of fine aggregate have an important effect on workability of fresh concrete and have an effect on strength and durability of hardened concrete. The effects of shape and texture of fine aggregate can be even much more important than the effects of coarse aggregate [QUIR03]. So, some studies have used fine aggregate from a river, with a predominance of rounded particles, suitable for concrete requiring high workability and fluency [SILV16]. As coarse aggregates, natural coarse aggregates with lower maximum sizes than in vibrated recycled concretes are usually used [SILV16, CORI11c].

Some recent works have used recycled fine aggregate [KOU09, CORI11c, CARR15, GESO15a, GUNE16] and recycled coarse aggregate [TANG16, GUNE16, BOUD16, GESO15b, KEBA15, TUYA14, PERE13, RAVI13, PAND13, GRDI10] obtained from crushed construction and demolition waste

[SILV16], with nominal sizes according to the requirements of natural aggregates [TANG13, FALE14, KEBA15, SEÑA16].

The particular characteristics of recycled aggregates are going to be as significant in SCRC as in RC. In fact, they can become even more remarkable since they influence fresh and hardened behaviour, and the former is a key issue in SCC.

Generally, the water absorption capacity of recycled aggregates affects the workability of new concrete. Additionally, their shape and texture depending mainly on the crusher type also affect the workability of concrete. Recycled aggregate is more porous and has rougher surface texture compared to the natural aggregate [TUYA14, SEÑA16]. Moreover, recycled aggregate leads to reduce the effective water content for the hydration process because the adhered mortar in the old ITZ tends to absorb a large amount of water during the initial mixing stage and, subsequently, creates loose ITZ in the hardened concrete [GUNE14]. These drawbacks which are mainly caused by the weak and porous ITZ of old cement mortar adhered to recycled aggregate impose limitation on the production of structural concrete, and especially on that of self-compacting concrete.

Some works have studied the possibility of treating recycled aggregates to improve their overall quality (the water glass and HCl pre-soaking treatment) [GUNE14], and fresh and hardened SCC properties were improved.

Cements, additions and admixtures

In the literature, it was found the use of ordinary Portland cement and mineral admixtures in SCRC, as happens in SCC. One purpose of the addition of powder in SCC is to densify the interface created between the aggregate and the Portland cement paste. In SCRC works, it was found the use of limestone filler [FAKI12, GRDI10, PERE14, KEBA15], calcareous filler [SEÑA16], silica fume [TANG16], fly ash [KOU09, TUYA14, GESO15b, TANG16, GUNE16] and ground granulated blast furnace slag [RAVI13, GESO15b]. Some authors have also used rubble powder [SILV16, SEÑA16, CORI11c]. Corinaldesi and Moriconi [CORI11c] founded that the main effect of powder from recycled aggregates was to reduce the workability of the paste over time (this was evidenced by the yield stress and plastic viscosity values).

The typical chemical admixtures found to produce SCRC were the polycarboxylate-based high range water reducing admixture, air-entraining admixture and high performance superplasticiser based on modified polycarboxylate-ether. The superplasticiser causing a high reduction of mixing water is the most usual.

5.2 Mix proportions

The SCRC mix proportions found in the literature usually fulfil the common and well-known mix proportions of SCC. Moreover, the proportions of SCRC mixes are made with replacement percentages of virgin aggregates by recycled aggregates in a range from 0% to 100%, as happens in vibrated recycled concrete.

The mix proportions cited in SCC section were fulfilled by the SCRCs designed in works related to this new concrete, such as lower coarse aggregate content, higher powder content (> 415 kg/m^3) or lower water to powder ratio (0.30-0.40) [SILV16, SEÑA16, BOUD16, CARR15, GESO15a, KOU09]. Moreover, all works agree in the fact that the high water absorption of recycled aggregates must be compensated.

As in SCC, to design SCRC it can be considered the concrete as a two phase material, the matrix phase (mortar phase) and the incrustations of coarse aggregates on this matrix (concrete phase) [NEPO12]. The design parameters of the mortar phase should be defined to obtain simultaneously the desired fresh and hardened properties of self-compacting concrete. Thus, the general approach would consist of selecting the materials, defining the reference grading curves for fine and coarse aggregates, studying mortars and, finally, studying concretes with percentages of recycled aggregate from 0 to 100% [PERE13].

5.3 Mixing procedure

The mixing procedure in self-compacting recycled concrete will be similar to that in vibrated recycled concrete to take into account the water absorption of recycled aggregates.

According to the SCRC literature review, in order to control the high absorption of recycled aggregates, the two different mixing procedures developed for vibrated recycled concrete are also used. The first one consists of working with the aggregates in their natural moisture state while increasing the amount of water incorporated in the mix to compensate up to a fixed percentage of the water absorption capacity [KOU09, PERE13, KEBA15]. The second procedure consists of pre-soaking recycled aggregates for a fixed time, such as 10 min [CARR15], 30 min [GUNE16, GESO15b], 120 min [TANG13] or 24 h [TANG16, YU14, TUYA14], or sprinkling them with water before adding to concrete [SEÑA16]. On the other hand, some authors use recycled aggregates in dry conditions to observe the effect of their water absorption on the SCC water and superplasticiser demand [PERE14, SILV16].

Furthermore, the mixing procedure of SCRC will be similar to that in self-compacting concrete to consider the required mixing time longer than in conventional vibrated concrete. Due to the amount and types of fine aggregates and admixtures, SCC in general, and SCRC in particular, always requires a greater mixing time than conventional concrete to be able to achieve proper mixture homogeneity [SEÑA16].

5.4 Fresh-state properties

Most of studies from the SCRC literature are specifically focused on the basic properties of hardened concrete and only verify that workability criteria for the fresh SCC are fulfilled.

In this way, the majority of works have studied the workability characteristics (filling ability, passing ability and resistance to segregation) through empirical tests as slump flow, L-box, V-funnel, J-Ring and sieve segregation [GRDI10, CORI11c, FAKI12, TUYA14, GUNE16, SILV16, SEÑA16]. However, not so much works have studied the rheological properties of SCRC. Some authors have measured the static yield stress and plastic viscosity of SCRC [CARR15, FALE14, KEBA15, GUNE16], but rheology and other issues as robustness and thixotropy have not been well studied yet.

Referring to the fresh properties of concrete, it was observed that when recycled coarse aggregate increases, it is necessary to add more superplasticiser to get a concrete that could be considered as self-compacting concrete [SILV16, TUYA14] or to use a mixing procedure that takes into account the high absorption capacity of recycled aggregates.

Thus, it was observed that the incorporation of recycled coarse aggregate slightly affects the slump flow of the mixes, proportionally to the percentage of replacement [SILV16, GRDI10]. This behaviour is due to two factors: the first is that recycled aggregates have a greater surface roughness after being subjected to processes of crushing compared with natural aggregate and, the second one, is that these type of recycled aggregate has a greater amount of fine particles resulting from the crushing process with the consequent requirement of more water [SAFI11]. These factors affect the slump flow of the SCRCs, especially when replacement of natural aggregates by recycled ones is close to 100%.

SCRCs with less to 50% of recycled coarse aggregate usually meet the criterion of the L-box ratio, showing a suitable passing ability. Mixes with high replacement percentages can be still within allowable passing ability limits although they may not achieve the L-box blocking ratio.

Authors have obtained that SCRC mixes are resistant to segregation and the segregation ratio of SCRC decreases with the increase in the recycled aggregate content (Figure II-41). This is attributed to the higher water absorption capacity of the recycled aggregate [TANG13].

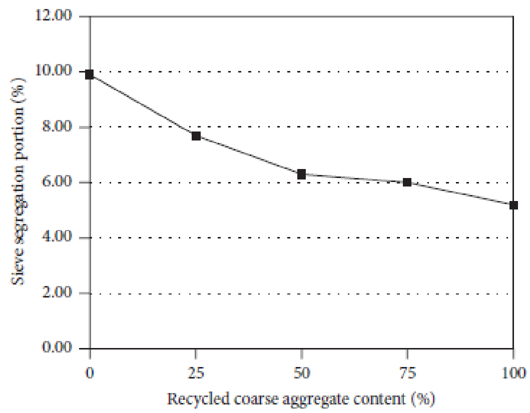


Figure II-41. Effect of recycled coarse aggregate on sieve segregation test [TANG16]

Therefore, the diameter and time of slump flow test, the blocking ratio of L-box test and the time of V-funnel test can be affected especially when replacement of natural aggregates by recycled coarse aggregates is close to 100%. This may be attributed to the rougher surface texture of recycled coarse aggregate compared to that of natural one, the angular shape and, possibly, its continued water absorption despite pre-wetting it or adding an extra quantity of water during mixing [TANG13, TUYA14].

Some authors have also studied the evolution over time of the empirical tests to observe possible losses of filling and passing abilities due to the incorporation of recycled aggregates in SCC [TANG16, TANG13, KEBA15, CARR15, KOU09]. These time-dependent losses increase with the recycled aggregate content. It is worth noticing that significant losses are observed when the replacement percentage is high (Figure II-42).

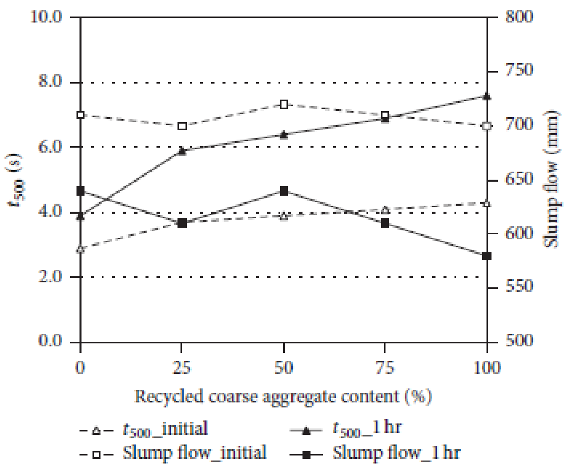


Figure II-42. Effect of recycled coarse aggregate on slump flow test [TANG16]

Regarding rheological parameters, the yield stress and the plastic viscosity increase as the recycled aggregate increases [CARR15, KEBA15]. Furthermore, both properties increase over time and even higher rise for high replacement percentages can be observed.

Finally, the density of SCC with recycled aggregates is lower than that of SCC with natural aggregates [SILV16]. Since the density of recycled aggregates is lower than that of natural aggregates due to the porous old cement mortar adhered to them, the fresh density of SCC mixes gradually decreases in terms of the increasing replacement percentage [GUNE16]. The reductions found for the total substitution of coarse aggregate were of 4%, in the same range of vibrated recycled concretes [RAVI13, GRDI10].

5.5 Hardened-state properties

The most studied hardened-state properties in SCRC have been the three basic mechanical ones: compressive strength, splitting tensile strength and modulus of elasticity. In general terms, the incorporation of recycled coarse aggregate decreases the mechanical properties of SCC.

The compressive strength of SCC decreases with the increase in the amount of recycled coarse aggregate [PAND13, SILV16, TUYA14, RAVI13, GESO15a, CORI11c]. As usually happens in vibrated recycled concretes, the use of recycled coarse aggregate in proportions of 25% to 50% does not negatively impact upon the compressive strength of SCC [TANG16, PERE13, YU14]. In fact, even up to the 100% recycled coarse aggregate, reductions in these parameters were less than 10% when compared to the control SCC [TANG16, PERE14, YU14].

The quality of recycled aggregate has a direct effect on the compressive strength. If the quality of the used aggregate is satisfactory (i.e. it shows a consistent composition), the differences in compressive strength between conventional SCC and SCRC can be small (Figure II-43). Replace the 50% of coarse aggregate was found to decrease the compressive strength for 3.88% and replace the 100% for 8.55% [GRDI10].

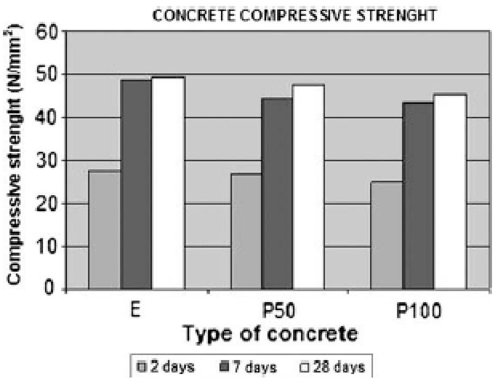


Figure II-43. Compressive strength of SCRC [GRDI10]

In some works where coarse and/or fine recycled fractions were used, the compressive strength decreases with the incorporation of recycled sand [GESO15a, KOU09]. Carro-López et al. [CARR15] obtained that the mix with 20% recycled sand showed a reduction of 8% of compressive strength, relative to the reference SCC, whereas the one with 100% recycled sand exhibited a reduction of 47%.

The literature results show that the use of recycled concrete coarse aggregate reduces splitting tensile strength of SCC [RAVI13, PAND13]. Some authors have obtained that the values of splitting tensile strength slightly decrease with the replacement of natural coarse aggregate by the recycled one [TUYA14], and the highest decrease is produced when the replacement is total [SILV16]. In fact, the use of recycled coarse aggregate in proportions of 25% to 50% does not negatively impact upon the splitting tensile strength of SCC [TANG16].

Thus, a decrease of 2.49-13.95% when 50-100% of recycled coarse aggregate is used [GRDI10] and even of 18%-23.2% [YU14] were found. This reduction of strength is caused by the changes in the concrete microstructure [GRDI10].

Also, the flexural strength of SCC decreases with the increase in the content of recycled coarse aggregate [PAND13, GESO15a].

On the other hand, the literature results show that the use of recycled concrete coarse aggregate reduces modulus of elasticity of SCC [RAVI13]. The modulus of elasticity for the 100% recycled coarse aggregate SCC was found to be notably reduced when compared to the conventional SCC [TANG16]. Pereira-de-Oliveira et al. [PERE14] concluded that the incorporation of recycled aggregate reduces the SCRC dynamic modulus of elasticity around 8% when compared to the self-compacting concrete with natural coarse aggregate.

Finally, the drying shrinkage of self-compacting concrete with recycled aggregates is much higher than that of concrete with natural aggregates [GESO15b]. Kou and Poon [KOU09], who used recycled coarse and fine aggregates, obtained that the drying shrinkage increases with an increase in the recycled fine aggregate but it can be controlled by the use of a lower water to cement ratio. This can be explained by the mortar adhering to the recycled fine aggregates which contributes to an increase in the volume of paste.

5.6 Durability

The self-compacting concrete with recycled coarse aggregate is more susceptible to penetration of water. As in vibrated recycled concrete, the lower quality of this aggregate due to the presence of numerous cracks and pores (aggregates and adhered mortar) generates an increase of effective porosity. This behaviour is more evident when higher percentages of recycled aggregate are used in the mixes of SCC [SILV16].

Thus, regarding water absorption of SCRC, the increase of the recycled aggregate quantity causes the increase of this property [TUYA14, PAND13]. The fact is attributed to the higher porosity of recycled aggregate compared to that of natural aggregate. Grdic et al. [GRDI10] obtained that the use of 50–100% of recycled coarse aggregate increases the water absorption for 0.15–0.37%.

The SCRC literature reveals that using recycled aggregates makes the self-compacting concretes more water permeable, irrespective of the size of recycled aggregates. It was also observed that this effect is more pronounced when the water to binder ratio increases [GESO15b]. As a result, water penetrates deeper into the SCCs containing recycled aggregates. However, some authors concluded that recycled aggregate incorporation did not significantly affect the SCC water permeability [PERE14, GRDI10].

Again, due to its high permeable and porous structure, incorporating recycled coarse and/or fine aggregate results in a systematic increase of chloride-ion permeability in SCRCs [GESO15b, RAVI13]. Kou and Poon [KOU09] found that the resistance to chloride-ion penetration of self-compacting concretes with 100% of recycled coarse aggregate and a percentage of recycled fine aggregate increases as this recycled fine aggregate content increases. On the other hand, the negative effect of recycled aggregates on the chloride-ion permeability remarkably decreases with the decrease of water to binder ratio and incorporating silica fume [GESO15b].

As a general conclusion, the SCRC literature indicates that the use of recycled coarse aggregate could improve the environmental aspects of SCC without significant impact on workability and strength characteristics when low replacement percentages are used (up to 50%). However, the study of SCRC is still at an early stage. This concrete requires more in-depth analysis by researchers looking into the fresh-state behaviour (especially the analysis of its rheology, robustness and thixotropy) and into the long-term mechanical and durability properties.

6 SPECIFIC OBJECTIVES

The main objective of this dissertation is to study the hardened and fresh behaviour of self-compacting recycled concrete, replacing different percentages of natural coarse aggregate with recycled concrete coarse aggregate.

The first general objective is to analyse the **hardened behaviour** (compressive strength, splitting tensile strength and modulus of elasticity) of SCRC. To do so, it is assumed that SCRC presents properties in hardened-state similar to those of its equivalent vibrated recycled concrete. Therefore, it is possible to study the hardened-state behaviour of SCRC by analysing that of vibrated recycled concrete with which there is more extensive experience.

Regarding this general objective, the specific objectives are as follows:

- The development of a database with international references related to the field of recycled concrete. The database will be developed considering works where the recycled coarse aggregate used is obtained from concrete waste (recycled concrete coarse aggregate). Furthermore, the works will be classified considering different mixing procedures ("Air-dry with extra-water-ADwEW", an extra quantity of water is added during mixing; "Pre-soaked-PS", recycled aggregate is pre-soaked immediately before mixing and "Air-dry without extra-water-AD", air-dry aggregates without any extra water but using a significant amount of superplasticizer to maintain workability).
- The prediction of some of the most important properties of structural vibrated recycled concrete (compressive strength, modulus of elasticity and splitting tensile strength) taking into account, not only the recycled percentage and the quality of the recycled aggregates used, but also the mixing procedure.
  - Regarding the compressive strength, the objective is to compare the compressive strength of conventional concrete with that of recycled concrete.
  - Regarding the modulus of elasticity and splitting tensile strength, there are three objectives: firstly, to compare these properties with those of conventional concrete. Secondly, to analyse whether or not it is necessary to adapt the prediction code expressions (adjusted for conventional concretes) to take into account the use of recycled aggregates, developing, if necessary, correction coefficients that allow engineers to predict recycled properties with the same approximation degree as with conventional concretes. Lastly, to optimize specific expressions to predict these properties in structural recycled concretes. Two different tools will be used to develop the expressions: multivariable regression and genetic programming.
- The demonstration that the adjustments obtained with vibrated recycled concrete can be applied accurately when analysing the behaviour of self-compacting recycled concrete. The objective is to prove that the mechanical properties of SCRC are affected by the incorporation of recycled aggregates to a similar extent as those of vibrated recycled concrete. This will confirm that the correction coefficients and the specific expressions adjusted with vibrated recycled concrete can be used to predict SCRC properties with the same approximation degree as in SCC.

The second general objective is to determine the effect of the incorporation of recycled concrete coarse aggregate on the fresh-state properties of self-compacting concrete and to study the time-dependent **rheological behaviour** of SCRC.

The specific objectives related to the workability and rheology of SCRC are the following ones:

- The corroboration that the relationships between empirical parameters and between empirical and rheological ones show the same tendency in conventional and recycled self-compacting concretes, and to define a workability box for a suitable SCRC fresh behaviour.
- The definition of the specificity of SCRC rheology. In fact, the objective is to show that this specificity will be related to the quantity of extra water necessary to compensate the recycled aggregate absorption during the mixing protocol and to the intrinsic characteristics of recycled coarse aggregate that modifies the mortar composition of the concrete.
- The analysis of the influence of the specificity of SCRC rheology on the time-dependent evolution of its fresh state behaviour.

The third general objective focuses on studying the capacity of SCRC to maintain workability characteristics and rheological properties over time when variations are imposed on some of the main constituent materials (water, superplasticiser and cement), i.e. analysis of **robustness**. The specific objectives are as follows:

- The determination of SCRC robustness analysing, through sensitivity parameters, which factors affect it to a greater extent.
- The definition, through a statistical approach, of which tests provide more sensitivity when robustness of a SCC mix, in general, and a SCRC mix, in particular, is evaluated.

The fourth general objective is to study the SCRC **thixotropy**, being the specific objectives the following ones:

- The analysis of the degree of thixotropy developed in SCRC mixes according to the following methods: structural breakdown curves at various rotational speeds, hysteresis loop flow curves and yield stress at rest.
- The evaluation of the effect of the structural build-up at rest (thixotropy) on interlayer bond strength using flexural tests and water permeability tests.

CHAPTER III
Experimental program

1 INTRODUCTION

This chapter describes the experimental program followed in the research. Firstly, how the self-compacting recycled concrete mixes were designed is described, along with their constituent materials in section 2 and mix proportions in section 3. Secondly, the mixing procedure is explained and lastly, the testing methods and protocols adopted to evaluate the hardened properties and quantify the rheology, robustness and thixotropy of self-compacting recycled concrete are described.

The first part of this work consisted of analysing the hardened-state behaviour (compressive strength, splitting tensile strength and modulus of elasticity) of self-compacting recycled concrete. To do so, it was assumed that self-compacting recycled concrete (SCRC) presents properties in hardened-state similar to those of its equivalent vibrated recycled concrete. Therefore, it is possible to study the hardened-state behaviour of SCRC by analysing that of vibrated recycled concrete with which there is more extensive experience. Then, it was decided to create a database including published results for vibrated recycled concrete, in order to draw general conclusions about the three aforementioned properties. Once this was carried out, the results obtained for vibrated recycled concrete were used to predict self-compacting recycled concrete behaviour (compressive strength, splitting tensile strength and modulus of elasticity) and the accuracy of predictions using this concrete was then analysed. Finally, these predictions were compared with experimental results.

The aim of the second part of this work was to study the fresh-state behaviour of self-compacting recycled concrete (SCRC).

To carry out both parts, a broad experimental program was prepared and divided into three working phases. It is summarised in Table III-1.

In the first phase, named **"Rheology"**, the objective was to discover the influence of the substitution percentage of natural coarse aggregate with recycled aggregate obtained from concrete waste on the workability and rheology of SCRC. Four types of self-compacting concrete were studied: a reference concrete and three recycled concretes. The replacement percentages of natural with recycled coarse aggregate were 20%, 50% and 100% (in volume). So, this first phase focuses on the relationship between the properties of fresh self-compacting recycled concrete obtained with a rheometer (such as yield stress and plastic viscosity) and those measured using empirical tests (slump flow, L-box, V-funnel, J-Ring and sieve segregation). All mixes were tested over time at 15, 45 and 90 min from water-cement contact. In this context, the research also studies the time-dependent fresh-state behaviour of SCRC.

Table III-1. Experimental program

Working phases	Fresh-state		Hardened-state
Phase 1: “Rheology” Phase 2: “Robustness”	Empirical tests	Slump flow V-funnel L-box J-Ring Sieve segregation	Compressive strength Density
	Rheological tests	Stress growth Flow curve	
Phase 3: “Thixotropy”	Empirical tests	Slump flow	Compressive strength Modulus of elasticity Splitting tensile strength Flexural strength Water permeability
	Rheological tests	Structural breakdown curves Hysteresis loop flow curves Yield stress at rest	

In order to control the high absorption of recycled aggregate, authors proposed two alternative procedures for producing recycled concrete. In the first, the recycled aggregate is added dry or with its natural moisture and its absorption is compensated with additional water. In the second, the recycled aggregate is added to the mix after being immersed in water for a pre-established period of time (usually 10 min). Current trends suggest that the first procedure leads to better behaviour than the second. In the “Rheology” phase, both procedures are studied and three mixing methods are used:

1. M1 method: aggregates are used in dry-state conditions and an extra quantity of water is added during mixing. This is calculated to compensate the recycled aggregate absorption at 10 min (i.e. 80% of that at 24 h).
2. M2 method: recycled aggregate is pre-soaked to up to 80% of its total water absorption capacity immediately before mixing.
3. M3 method: recycled aggregate is used with 3% natural moisture and again an extra quantity of water is added during mixing according to the same criterion as the M1 method.

In the second phase, known as **“Robustness”**, the experimental program was carried out to evaluate the robustness of SCC containing recycled aggregate. Two series of SCC mixes with different percentages of recycled concrete coarse aggregate (0%, 20%, 50% and 100%) were studied: one series with the aggregate used in dry-state conditions (M1 method) and the other incorporating it in the mixer with 3% moisture (M3 method). The analysis focused on the capacity of SCRC to maintain workability and rheological properties over time while variations in water (±W = ±3%), superplasticiser (±S = ±5%) and cement (±C = ±3%) were imposed independently.

To analyse the hardened-state behaviour of self-compacting recycled concrete, in both working phases, the density of fresh and hardened concrete and compressive strength at 3, 7 and 28 days were determined for each mix.

In the third phase, known as **“Thixotropy”**, several testing methods and protocols were used to evaluate the degree of thixotropy of SCRC mixes (they were produced with the aforementioned replacement percentages and according to the M1 method). In this phase, the influence of thixotropy on SCRC mechanical behaviour, bond strength and water permeability that can be developed between SCRC layers for various delay times, was evaluated. In this third phase, to analyse the hardened-state behaviour, the compressive strength, splitting tensile strength and modulus of elasticity at 28 days were measured for each mix.

2 MATERIALS

The following materials were used in this research, all of which were readily available in Spain.

2.1 Cement, filler, superplasticiser and water

Cement and filler: Portland cement without admixtures labelled CEM-I 52.5 R according to European Standard EN 197-1 [EN197-1] and a limestone filler were used as the powder fraction. Properties of both materials can be seen in Table III-2, Table III-3 and Table III-4.

Table III-2. Physical properties of cement and limestone filler

Physical property	**Cement**		**Limestone filler**
	Value	**Limit** [RC-08]	**Value**
Density	3.11 t/m³	–	2.71 t/m³
Loss on ignition (1000 ºC)	3.2 %	≤ 5 %	41.8 %
Specific surface (BET)	1.04 m^2/g	–	1.77 m^2/g
Initial setting time [EN196-3]	190 min	≥ 40 min	–
Final setting time [EN196-3]	260 min	≤ 12 h	–
Soundness [EN196-3]	0.3 mm	≤ 10 mm	–

Table III-3. Mechanical properties of cement

Mechanical property	**Value**	**Limit** [RC-08]
Initial strength (at 2 days) [EN196-1]	45.5 MPa	≥ 28 MPa
Strength (at 28 days) [EN196-1]	64 MPa	≥ 50 MPa

Table III-4. XRF analysis of cement and limestone filler

Oxide/Element	**% mass (Cement)**	**% mass (Limestone filler)**
CaO	64.1	54.7
SiO_2	15.9	1.6
SO_3	4.3	0.18
Al_2O_3	4.1	0.46
Fe_2O_3	4.0	0.22
K_2O	1.3	0.12
MgO	1.1	0.47
SrO	0.78	0.046
Na_2O	0.27	-
TiO_2	0.25	-
ZnO	0.12	0.009
Cl	0.059	-
P_2O_5	0.050	-
MnO	0.047	-
CuO	0.040	0.010
ZrO_2	0.036	0.003
PbO	0.022	-

Superplasticiser: two modified polycarboxylate superplasticisers were used. In the “Rheology” and “Robustness” phases, the superplasticiser used was Sika ViscoCrete-70, and in the “Thixotropy” phase, it was changed to Sika ViscoCrete-500.

These kinds of superplasticisers are used to produce high performance, high strength and flowable concrete. They provide concretes with a very low water content and high fluidity, optimal internal cohesiveness, no segregation and bleeding, high performance in durability and impermeability, and fast development of strength (a significant increase of early strength and 28 days strength).

Both superplasticisers are very similar. Their description and specifications are listed as follows:

- Visual appearance: brown liquid.
- Chemical composition: a modified polycarboxylate.
- Density: 1.08 kg/l (Sika ViscoCrete-70) – 1.09 kg/l (Sika ViscoCrete-500).
- PH: approximately 4.5 (Sika ViscoCrete-70) – 5 (Sika ViscoCrete-500).
- Cl^-: no chlorides.
- Solid content: 32%.
- Storage time: 12 months since the production date.
- Dosage: between 0.5% and 1.5% by weight of cement.

Figure III-1. Superplasticiser used

Water: according to the Spanish standard [EHE08], the water used cannot contain any harmful component that can affect concrete properties. Drinking water from the tap available in the laboratories of the *Escuela Técnica Superior de Ingenieros de Caminos, Canales y Puertos* (School of Civil Engineering, Channels and Ports) and in the *Centro de Investigación e Innovación Tecnológica en Edificación e Ingeniería Civil* (Center for Research and Technological Innovation in Building and Civil Engineering), University of A Coruña, was used in all mixes.

2.2 Aggregates

Natural aggregates: as fine aggregate (NFA), a limestone sand with a nominal size of 0-4 mm and a fineness modulus of 4.19 was used. A crushed granitic coarse aggregate (NCA) with a nominal size of 4-11 mm and a fineness modulus of 7.14 was also used (Figure III-2).

Recycled aggregate: the size fraction used was 4-11 mm with a fineness modulus of 6.47. This recycled coarse aggregate (RCA) was obtained from real demolition debris of structural concrete. It was made up mainly of concrete and stone (Figure III-3 and Figure III-4).

Figure III-2. Natural fine aggregate (left) and natural coarse aggregate (right)

Figure III-3 exhibits the composition of this recycled coarse aggregate according to EN 933-11 [EN933-11]. On the basis of these results, it can be classified as recycled coarse aggregate from concrete demolition waste and named RCA (recycled concrete aggregate) using the BS 8500:02 classification [BS8500:02], as type II according to the RILEM [RILEM94], as type I according to DIN 4223 standards [ACHE06] and as GBSB-II according to Belgium specifications [VINC94].

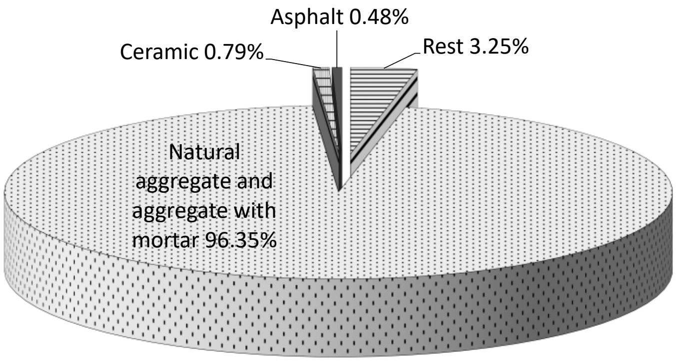


Figure III-3. RCA composition

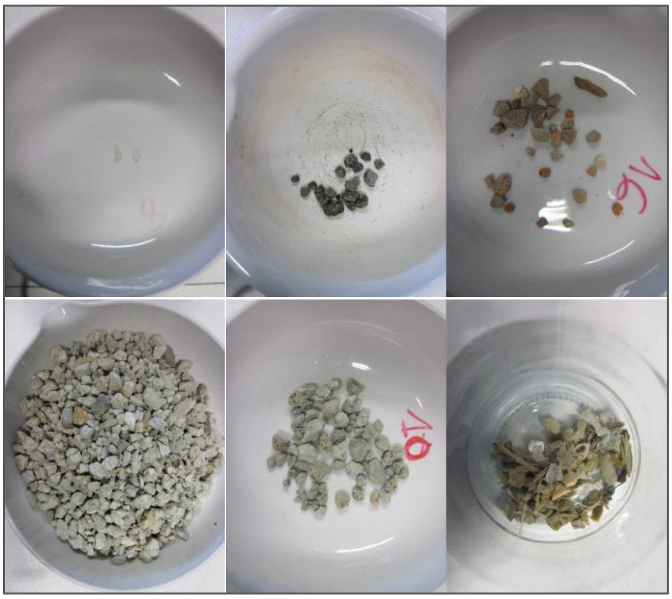


Figure III-4. Constituents of RCA

Table III-5 summarizes the basic properties of the aggregates used.

Table III-5. Basic properties of aggregates

Property	NFA	NCA	RCA
Fineness modulus [EN933-1]	4.19	7.14	6.47
Fines percentage [EN933-1] (%)	8.40	0.84	3.00
Saturated-surface-dry density [EN1097-6] (t/m^3)	2.72	2.56	2.34
Water absorption [EN1097-6] (%)	1.00	1.12	6.96
Flakiness index [EN933-3] (%)	-	5.41	5.33
Shape	Crushed	Crushed	Crushed

All tests regarding the characterization of aggregates (Figure III-5, Figure III-6, Figure III-7 and Figure III-8), were carried out according to the European Standards.

Figure III-5. Preparation of aggregate samples for characterization

Figure III-6. Determination of particle size distribution. Sieving method

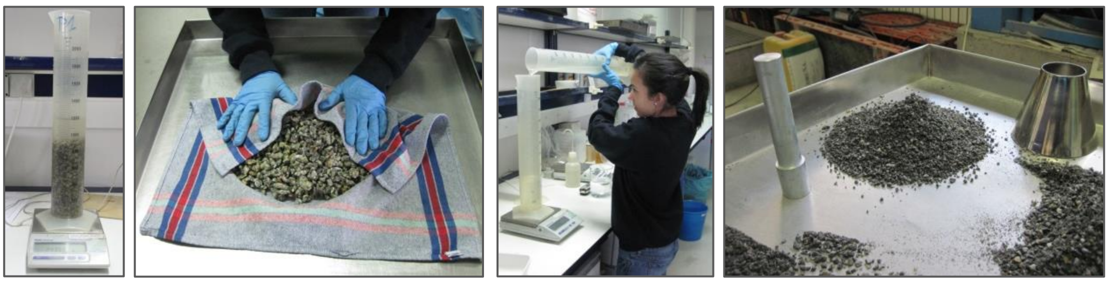


Figure III-7. Determination of particle density and water absorption

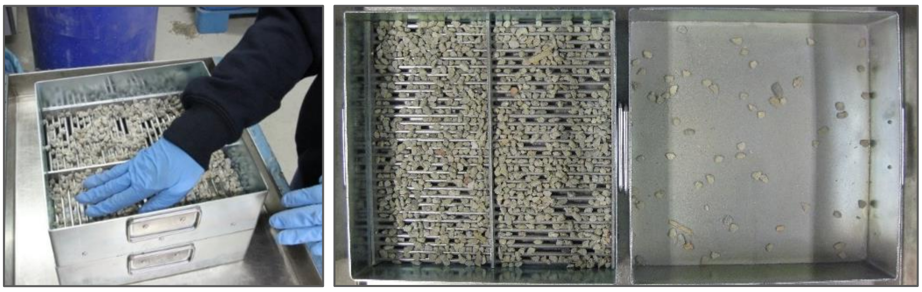


Figure III-8. Determination of flakiness index

In Figure III-9, the grading curves of each aggregate are displayed, showing that the recycled and natural coarse aggregate present similar particle size distribution (Figure III-10).

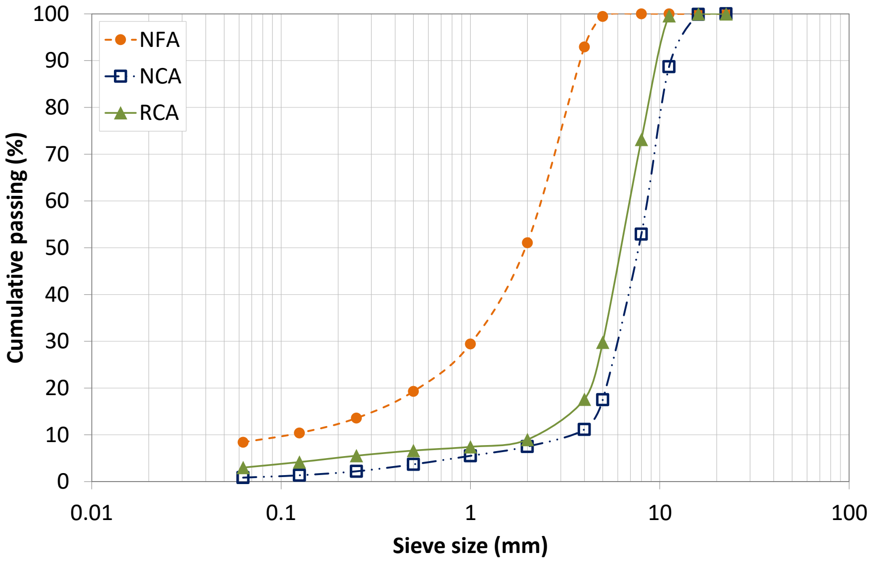


Figure III-9. Aggregates grading

Figure III-10. Particle size distribution of RCA

Many researchers have studied the influence of aggregates on the rheological properties of fresh concrete. They conclude that knowledge of the solid volume fraction, maximum packing fraction ($Ø_{max}$), shape and particle size distribution is highly important [MAHA08].

In this work, both natural and recycled aggregates are crushed aggregates. The shape of recycled coarse aggregate is very similar to that of natural coarse one. The former may be considered as an angular aggregate (little evidence of wear on the particle surface) and the latter as a sub-angular aggregate (evidence of some wear, but faces untouched). Both can be defined as aggregates with high sphericity (Figure III-11).

Regarding surface texture, the recycled coarse aggregate is more porous and rougher than the natural one due to the adhered mortar (Figure III-12). It was also observed that the content of fines in the recycled coarse aggregate was higher than that of the natural coarse one (Figure III-9).

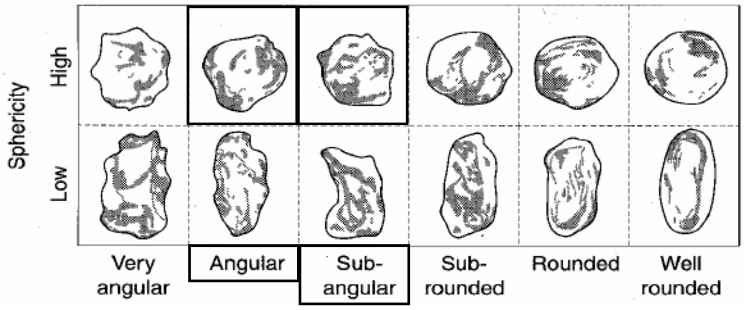


Figure III-11. Shape of coarse aggregates used [QUIR03]

Figure III-12. Texture of natural (left) and recycled (right) coarse aggregate

Moreover, in Figure III-13, the maximum packing fraction ($Ø_{max}$) of different granular skeletons (designed mixing the natural coarse and fine aggregate with the recycled one using different percentages) is plotted.

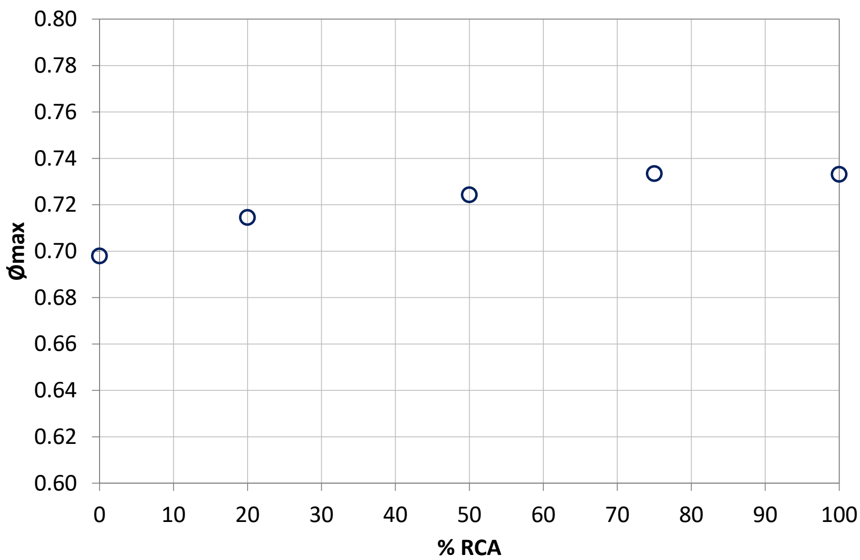


Figure III-13. Maximum packing fraction ($Ø_{max}$) of different granular skeletons

Although both recycled and natural coarse aggregates used are crushed aggregates, it is expected that the higher roughness of the former leads to a worse packing density (and, therefore, a worse maximum packing fraction). However, the results indicate that $Ø_{max}$ is quite similar in all mixes (Figure III-13), although a slight ascending trend can be noted with the increase in percentage of recycled aggregate due to its slightly better shape and its greater content of fines, as aforementioned.

So, in general terms, these similar packing properties can be explained by the fact that shape and therefore packing are mostly imposed by processing and that both aggregates were crushed. Some deviations can be obtained for brittle aggregates, however, as structural self-compacting recycled concrete was designed in this study, the recycled concrete coarse aggregate used is a high quality recycled aggregate obtained from concrete waste with a low quantity of impurities (Figure III-3). Therefore, the grading curve and shape, variables that influence $Ø_{max}$, are very similar to those of natural coarse crushed aggregate.

Another important property that should be considered when recycled aggregates are used is their water absorption. Water absorption capacity develops over time. Hence, EN 1097-6 [EN1097-6] establishes that it should be measured after soaking aggregates in water for at least 24 h.

In addition to this standard absorption test, in this work, continuous measurement of this property over time was conducted (Figure III-14). The procedure consisted of measuring, by hydrostatic weighing, the mass variations of a sample immersed into a thermo regulated bath.

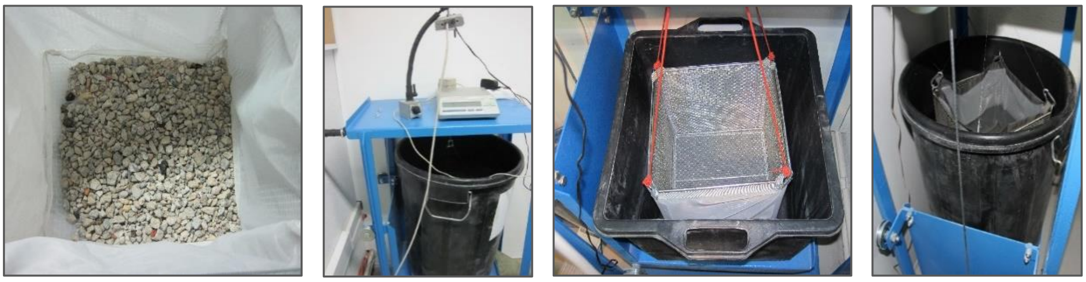


Figure III-14. Water absorption measurement using hydrostatic weighing

The aggregate sample was dried in an oven at a temperature of 110 ± 5 ^{o}C until the difference in mass was less than 0.1%. After drying, the sample was placed in a perforated basket (stainless steel density basket for hydrostatic weighing of 250 x 250 x 250 mm in dimension and with a perforated mesh of 5 mm) which was hung from a balance using a non-elastic wire.

Firstly, the mass of the system was continuously recorded and this recorded value was the mass of oven-dry aggregate sample in air with a balance accuracy of 0.1 g. Then, the thermo regulated bath was moved vertically using a removable tray in order to immerse the sample into the water bath at 20 °C (Figure III-14), assuming that the first value recorded after soaking was the mass of the oven-dry aggregate sample in water.

The results show that, at the usual reference time of 10 min [GONZ11b], recycled coarse aggregate absorbs water to up to 80% of that absorbed at 24 h (Figure III-15).

3 MIX PROPORTIONS

In this research, four types of self-compacting concretes were studied: a reference concrete and three recycled concretes replacing the natural coarse aggregate with recycled concrete coarse aggregate.

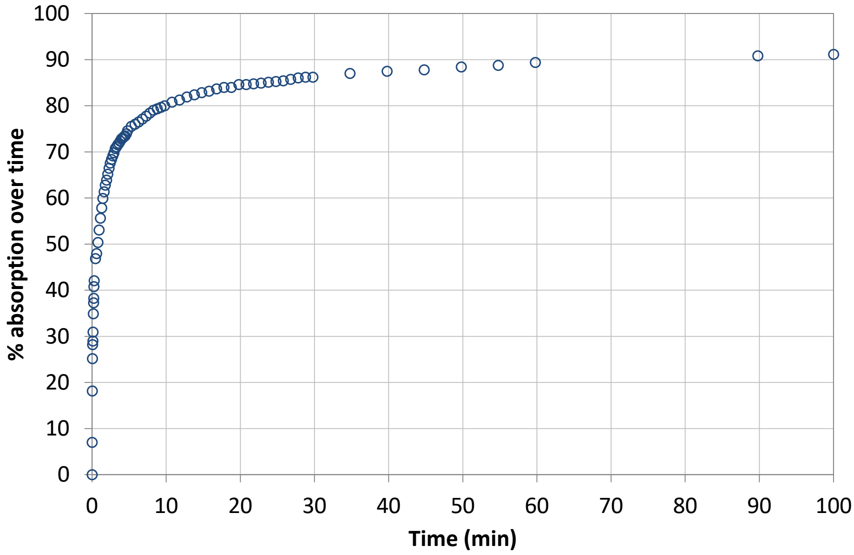


Figure III-15. RCA water absorption evolution from 0 to 100 min

In order to define some of the most important parameters of the reference SCC mix, different guidelines and databases of fresh and hardened state properties of SCC [VILA09, JIN02, DOMO07] were used.

Furthermore, it is suggested that mortar plays an essential role in self-compacting concrete design. There appears to be a good relationship between mortar and concrete properties, that is, most of the SCC properties may be related to those of mortar. This can reduce the number of tests on concrete and shorten the whole mix proportion adjustment phase. Also, mortar tests were used in the process to determine the dosage of superplasticiser and the water to cement ratio of the reference SCC mix.

3.1 Mix design parameters from databases

The self-compacting concrete technology started with Okamura's design method [OKAM03] and it has been increasingly developed in recent years. Therefore, many SCC dosages have been published in scientific papers and although tested in a laboratory, they are in agreement with those used in field-scale production [DOMO06]. Table III-6 shows a statistical summary of 627 mix compositions gathered by Vilanova-Fernández [VILA09]. This data agrees with Domone's results [DOMO06] where the mean coarse aggregate content was 31.2% in volume and the mean powder content was 500 kg/m^3, results that have also been found by Jin [JIN02]. The European Guidelines for Self-Compacting Concrete [EFNARC05] refer to a coarse aggregate content ranging from 750 to 1000 kg/m^3 and a powder content ranging from 380 to 600 kg/m^3.

Table III-6. Statistical summary of the mix content of SCC (data from [VILA09])

Mix content (kg)	Cement	Addition	Water/ cement	Water/ powder	Paste	Sand	Gravel
Maximum	665.0	490.0	1.34	0.80	1066.0	2625.0	1775.0
3rd quartile	450.0	225.0	0.60	0.40	800.0	900.0	900.0
Mean	368.5	158.2	0.51	0.34	718.1	858.8	806.6
Median	365.0	160.0	0.48	0.33	720.0	825.0	806.0
1st quartile	300.0	125.0	0.40	0.25	650.0	700.0	700.0
Minimum	133.0	0.0	0.26	0.21	429.2	478.0	267.0

Using these databases, it was decided to define a reference self-compacting concrete fulfilling the following mix proportions for 1 m^3: 400 kg of cement, a filler mass to cement mass ratio of 0.45 and 300 L of coarse aggregate. Once this data was defined, the other parameters (water to cement ratio and quantity of superplasticiser) were defined using equivalent mortar analysis. Based on this data, the equivalent mortar volume of the SCC is 700 L.

3.2 Mix design parameters from equivalent mortar analysis

Although concrete tests are necessary to ensure that the required SCC properties are achieved, it is well accepted that mortar tests provide helpful information, including the compatibility and suitable dosage of superplasticiser, workability and stability of the mixes, and early strength gain [CHAI97].

Mortar tests are versatile, easy to carry out and, hence, some researchers aim to deduce a mortar from a concrete composition. Then, fresh behaviour can be studied with the mortar instead of the concrete and in this manner, the amount of concrete batches can be reduced and experimental testing programs can be speeded up.

Schwartzentruber and Catherine [SCHW00] suggest using the concrete-equivalent-mortar (CEM) method to study the rheology of fresh concrete with the assumption that the rheological properties of CEM can be correlated with those of the corresponding concrete. When the CEM composition is determined, the following main relationships regarding the original concrete composition should be kept constant: cement and filler content, water/cement ratio and fine aggregate content. Regarding coarse aggregate fractions (those greater than 5 mm), they are replaced by an equivalent quantity of sand. As all friction phenomena is considered to take place at the cement paste / aggregate interface, the total specific area of aggregate is a fundamental variable that should be taken into account. Therefore the sand quantity is calculated in terms of specific surface area (to achieve the same total surface area of the coarse aggregates replaced [RUBI13]) to take into account the amount of water and fine particles that can be adsorbed onto the aggregate surface during mixing [ASSA09].

However, other simple methods have also been used. Actually, SCC can be described as a multiphase material in which coarse aggregate is suspended in a highly flowable mortar. Thus, other researchers have considered that the equivalent mortar can be obtained directly from the SCC compositions without taking the coarse aggregate into account [OKAM03]. With this equivalent-mortar (EM), the optimum water/powder ratio and superplasticiser dosage of the SCC can be determined, and the flow properties and segregation resistance controlled.

In any case, several approaches have been developed to correlate equivalent mortar with concrete. Nepomuceno et al. [NEPO12] suggested a method which is a generalization of that proposed by Ouchi et al. [OUCH98]. This method uses two parameters, Gm and Rm, measured in mortars, which are correlated with the slump flow and the V-funnel time of concrete. Other studies have also been carried out to define the mortar properties for successful SCC, as well as the relationships between various properties of mortar and concrete [JIN02]. In general, it is well accepted that there is a very strong relationship between the spread of mortar and the slump flow of concrete. However, the relationship between the mini-funnel time of mortar and the V-funnel flow time of concrete showed greater scatter [CHAI97, JIN02].

Therefore, in this work, at the adjustment phase of SCRC composition, equivalent mortars (EM) were firstly tested in fresh-state with the mini-slump flow test (mini-cone) and the mini-funnel test (Figure III-16). Both tests were used together to select a suitable water/powder ratio and superplasticiser dosage.

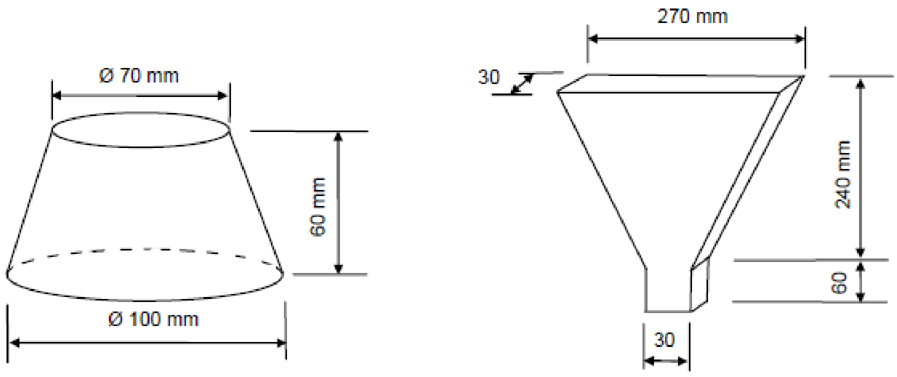


Figure III-16. Mini-cone (left) and mini-funnel (right) dimensions

The apparatus for the mini-slump flow test consists of a mould in the form of a frustum of a cone, 60 mm in height with a diameter of 70 mm at the top and 100 mm at the base. The cone is placed at the centre of a metal plate and is filled with the mortar. Immediately after filling, the cone is then lifted and the paste spreads over the plate. Then, the average diameter of the spread is measured (Figure III-17).

Figure III-17. Mini-slump flow test

The dimensions of the mini-funnel are shown in Figure III-16. The funnel is filled with 1.1 litres of mortar and then, the gate is opened and stop-watch started, both simultaneously (Figure III-18). The watch is stopped when light first appears when looking down into the funnel from above. The flow time is then read.

Figure III-18. Mortar mixer (left). V-funnel (right)

According to the mix parameters fixed using databases, the equivalent mortar volume was 700 L and was made of 400 kg of cement and a filler mass to cement mass ratio of 0.45. Then, the trial mortars were designed with a cement content of 571.43 kg and a filler content of 257.14 kg for 1 m^3 of equivalent mortar.

Different water to cement (w/c) ratios, from 0.40 to 0.50, also different superplasticiser dosages, from 0.80% to 1.70% (percentage of superplasticiser by weight of cementitious materials in the mix, % sp), were tested (Table III-7).

Table III-7. Mortar mixes and their rheological properties (mini-slump and mini-funnel)

Mix	w/c	% sp	Mini-slump (mm)	Mini-funnel (s)
1	0.40	1.60	277	16.40
2	0.50	1.60	380	4.70
3	0.45	1.60	370	8.70
4	0.43	1.60	323	10.70
5	0.45	1.40	322	9.10
6	0.50	1.20	345	5.34
7	0.50	0.80	295	3.90
8	0.45	1.50	315	10.16
9	0.45	1.20	300	8.25
10	0.45	1.40	315	10.32
11	0.45	1.20	308	9.09
12	0.45	1.00	287	9.53
13	0.43	1.40	273	12.51
14	0.43	1.50	315	10.07
15	0.43	1.20	260	11.38
16	0.40	1.80	313	12.15
17	0.46	1.70	350	5.58

As aforementioned, there are differences among researchers' criteria for specifying the target values for mini-slump flow and mini-funnel times in the equivalent mortar, that can lead to suitable slump flow and V-funnel values in concrete. These differences are caused by different types of materials and mix proportions used, especially coarse and fine aggregate types and contents.

For example, Chai [CHAI97] concluded that a mortar flow of at least 300 mm is required to obtain a concrete slump flow of over 650 mm. Regarding mini-funnel time, he suggested a value between 2-10 s when the maximum aggregate size in concrete is 10 mm (a value near the lower limit being preferred) and 4-10 s when it is 20 mm. Jin [JIN02] also concluded that a mortar flow of at least 300 mm is required to obtain a concrete slump flow of over 650 mm. This author determined a mortar funnel time between 3-6 s to obtain a concrete V-funnel time between 4-10 s. However, Nepomuceno [NEPO12] proposed a mini-slump flow range of 251-263 mm and a mini funnel time range of 7.7-8.7 s.

In Figure III-19, mortar test results (mini-funnel and mini-slump) can be observed. The equivalent-mortar was then selected taking into account the limits suggested by the aforementioned authors [CHAI97, JIN02], considering the similarities of coarse aggregate content and sand volume ratio.

Therefore, the mortar selected showed a w/c ratio of 0.46 and superplasticiser dosage of 1.7%. The equivalent mortar selected was that sited in the middle of the area defined by these authors.

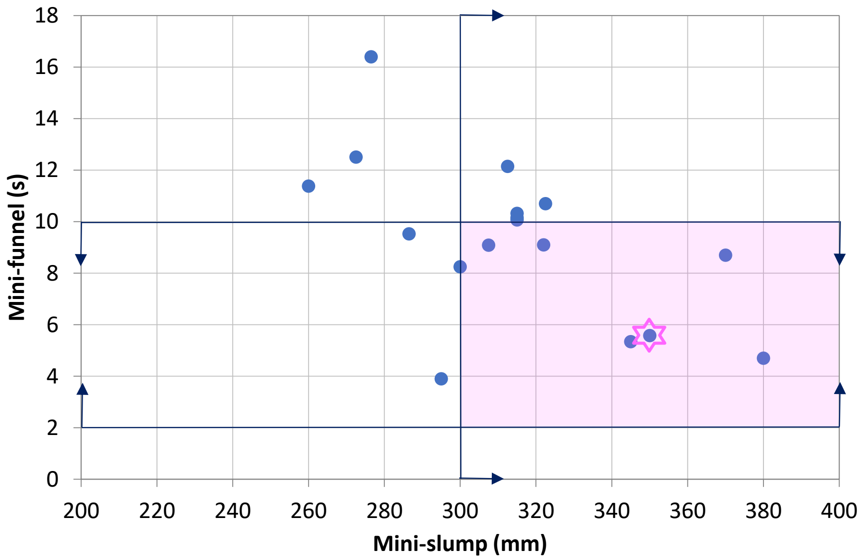


Figure III-19. Mini-slump vs. Mini-funnel of mortar mixes. Equivalent-mortar selection

3.3 Concrete mix design

With the results obtained from databases and from equivalent mortar analysis, the reference SCC was finally designed (Table III-8). The volumetric content of natural coarse aggregate was equal to 30% and the sand/mortar ratio was 0.45 by volume. The recycled concretes were obtained replacing the natural coarse aggregate with recycled aggregate, using volume replacements of 20%, 50% and 100%.

Table III-8. Mix proportions (1 m³) – "Rheology" and "Robustness" phases

Concrete SCRC	% RCA			
Dosage	**0%**	**20%**	**50%**	**100%**
Cement, c (kg)	400.00	400.00	400.00	400.00
Filler, f (kg)	180.00	180.00	180.00	180.00
Water, w (kg)	184.00	184.00	184.00	184.00
Natural sand (kg)	865.59	865.59	865.59	865.59
Natural coarse aggregate (kg)	768.00	614.40	384.00	0.00
Recycled coarse aggregate (kg)	0.00	140.40	351.00	702.00
Effective w/c (M1 and M3 methods)	0.46	0.46	0.46	0.46
Effective w/c (M2 method)	0.46	0.46	0.48	0.52
Superplasticiser/(c+f) (%)	1.70	1.70	1.70	1.70
w/(c+f) (M1 and M3 methods)	0.32	0.32	0.32	0.32
w/(c+f) (M2 method)	0.32	0.32	0.33	0.36

Some adjustments were needed in the "Thixotropy" phase due to the change in superplasticiser. The modifications only affected the w/c ratio and the superplasticiser dosage (Table III-9).

Table III-9. Mix proportions (1 m³) – "Thixotropy" phase

Concrete SCRC	% RCA			
Dosage	0%	20%	50%	100%
Cement, c (kg)	400.00	400.00	400.00	400.00
Filler, f (kg)	180.00	180.00	180.00	180.00
Water, w (kg)	196.00	196.00	196.00	196.00
Natural sand (kg)	832.76	832.76	832.76	832.76
Natural coarse aggregate (kg)	768.00	614.40	384.00	0.00
Recycled coarse aggregate (kg)	0.00	140.40	351.00	702.00
Effective w/c	0.49	0.49	0.49	0.49
Superplasticiser/(c+f) (%)	1.80	1.80	1.80	1.80
w/(c+f)	0.34	0.34	0.34	0.34

4 MIXING PROCEDURE

As aforementioned, three mixing methods were used for concrete fabrication:

1. M1 method: aggregates were used in dry-state conditions and an extra quantity of water was added during mixing. This was calculated to compensate the recycled aggregate absorption at 10 min (i.e. 80% of that at 24 h).
2. M2 method: recycled aggregate was pre-soaked to up to 80% of its total water absorption capacity immediately before mixing.
3. M3 method: recycled aggregate was used with 3% natural moisture and, again an extra quantity of water was added during mixing according to the same criterion as in the M1 method.

4.1 Materials preparation

The first step was to dry all aggregates. The natural coarse aggregate was dried using electrical equipment (Figure III-20).The fine natural aggregate was also dried with said equipment and then an air-drying procedure was also applied (Figure III-21).

Figure III-20. Drying process with electrical equipment of gravel (left) and sand (right)

Figure III-21. Air-drying procedure of sand

Samples were intermittently tested to control the moisture content of aggregates and when dry-state conditions were achieved they were put into bags (Figure III-22).

Figure III-22. Storage of aggregates

Recycled aggregate was dried by combining the use of the same electrical equipment, followed by its introduction into an oven (Figure III-23).

The preparation of recycled aggregate with a natural moisture level (M3 method) of 3% required an even more controlled procedure (Figure III-24). Preliminary tests were carried out to investigate the oven-drying evolution of this aggregate. The objective was to find out how many hours were necessary to dry it up to a moisture level of about 3%, whereby the moisture content could always be considered a natural condition.

Figure III-23. Drying process of recycled aggregate

Firstly, recycled aggregate was divided into big samples which were put into containers. Each one of them was tested to find its initial moisture. Secondly, they were oven-dried for a precise time according to their initial moisture and their known oven-drying evolution. Thirdly, they were put into bags and their moisture was measured once again. If the moisture content was slightly below the target of 3%, the corresponding water was added. If it was above, they were reintroduced into the oven for another period, fixed according to the moisture measured. Finally, during concrete fabrication according to the M3 method and before each mixing, a sample of recycled aggregate was taken to confirm its moisture.

Figure III-24. Recycled aggregate preparation for M3 method

In the case of the pre-soaking procedure (M2 method), the recycled aggregate in dry-state conditions was immersed in water 10 min immediately before mixing, and then it was allowed to drain to reach 80% of its water absorption capacity (Figure III-25). To achieve this objective, its weight was controlled taking into account not to exceed 5% of the weight corresponding to the recycled aggregate at 80% of its water absorption capacity. This data was used to calculate the effective water to cement ratio of each concrete. As can be seen in Table III-8, the M2 method introduced some variations in the effective w/c ratio of mixes, with the 50% and 100% replacement percentages being noteworthy.

Figure III-25. Pre-soaking procedure of recycled aggregate

On the days prior to carrying out each concrete mix, all needed materials were weighed and kept in the laboratory (Figure III-26).

Figure III-26. Materials preparation

4.2 Temperature and humidity

To control the environmental conditions throughout the experimental phase, a continuous record of temperature and humidity was made. Figure III-27 shows these values from May 2014 (05/14) to May 2015 (05/15).

The temperature of the laboratory varied from 7 ^{o}C to 24 ^{o}C and the relative humidity was kept between 60% and 94%. Hence, the average values were 16 ^{o}C and 77% respectively.

Regarding each particular working phase, the average temperature was 20 ^{o}C and the average humidity was 77% throughout the “Rheology” and “Robustness” phases. In the “Thixotropy” phase, the average temperature was lower, approximately 12 ^{o}C, and the relative humidity was kept around the same average value of 77%.

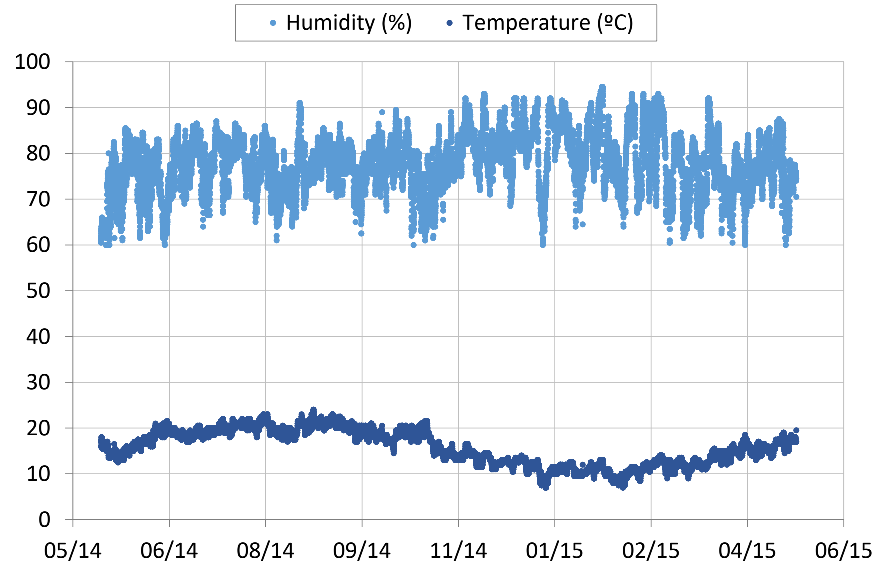


Figure III-27. Environmental conditions of laboratory. Temperature and humidity

4.3 Mixing protocol

The mixes were prepared in a planetary mixer with a vertical axis (Figure III-28), with a capacity of 250 litres. It is located in the *Centro de Investigación e Innovación Tecnológica en Edificación e Ingeniería Civil* (Center for Research and Technological Innovation in Building and Civil Engineering) of University of A Coruña. In the “Rheology” and “Robustness” phases, batches of 100 litres were produced for each type of concrete. In the “Thixotropy” phase, they were of 120 litres.

Figure III-28. Mixer used

As aforementioned, recycled concretes were produced by pre-soaking recycled aggregate (M2 method, Figure III-30) or adding an extra quantity of water during mixing. This was calculated to compensate the recycled aggregate absorption at 10 min (i.e. 80% of that at 24 h), which was used in dry-state conditions (M1 method, Figure III-29) or with 3% natural moisture (M3 method, Figure III-31).

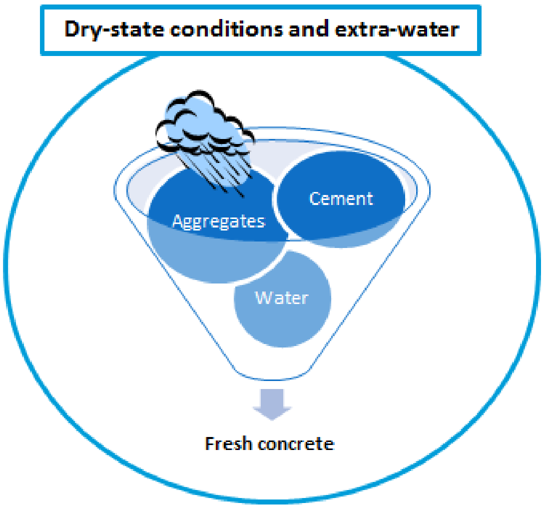


Figure III-29. M1 method

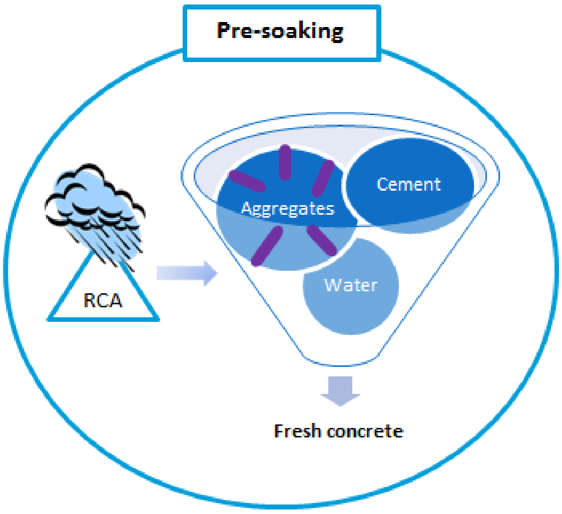


Figure III-30. M2 method

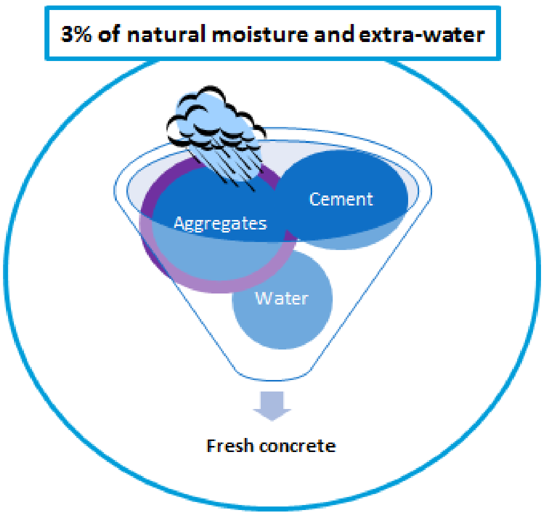


Figure III-31. M3 method

The mixing protocol is shown in Figure III-32. The same sequence was followed in all working phases. Firstly, the aggregates (sand and coarse aggregates) were mixed with the extra water (that calculated to compensate the recycled aggregate absorption at 10 min) for 2 min and then left to rest for another 8 min. This was done in the M1 and M3 methods. In the pre-soaking method (M2 method), the rest period from the second to the tenth minute was removed.

The cement was added along with the filler after the first 10 min. After 2.5 min of mixing, water was added (98.5%). This cement-water contact is considered the reference time for performing all fresh concrete tests. After 2 min of mixing, the superplasticiser and the remaining water were introduced. The mixing was continued for another 3 min, the concrete was left to rest for 2 min and finally mixed again for an additional 2 minutes. Then the concrete was poured into the rheometer and into different buckets. It was left there to rest until its testing age.

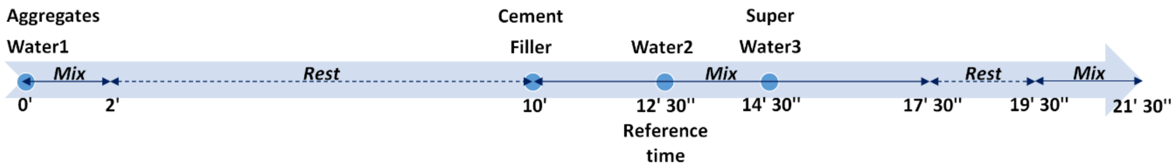


Figure III-32. Mixing protocol

5 TESTING PROGRAM

5.1 Phase 1 and phase 2: Rheology and Robustness

Extensive laboratory work was conducted to produce 52 self-compacting recycled mixes. The testing program used was the same for the "Rheology" (10 mixes) and "Robustness" phases (42 mixes).

5.1.1 Fresh-state tests

The experimental program developed to study the fresh-state behaviour of each SCRC mix is summarised in Figure III-33. A controlled and well organised testing procedure was carried out with the aim of obtaining consistent and reliable test results.

The fresh behaviour was investigated using empirical tests related to the concept of workability and rheological tests related to the concept of fluid behaviour.

5.1.1.1 Empirical tests

The workability characteristics of the investigated mixes were determined at 15, 45 and 90 min from the contact time of water with cement (*the reference time*). Two and a half minutes before these three times, the concrete was remixed for 30 s.

Five empirical tests were selected to study the key properties of the self-compacting behaviour (filling ability, passing ability and resistance to segregation). These were: the slump flow test [EN12350-8], the V-funnel test [EN12350-9], the L-box test [EN12350-10], the J-Ring test [EN12350-12] and the sieve segregation test [EN12350-11].

Slump flow test

The slump flow test aims to investigate the filling ability of SCC. In fact, it is considered the reference method for evaluating SCC deformability in the absence of obstacles. It measures two parameters: the horizontal flow diameter (SF) and the time needed to reach 500 mm flow (t500). The former indicates the free, unrestricted deformability and the latter indicates the rate of deformation within a defined flow distance. In this test, the segregation resistance can be detected by visually evaluating the presence of visible bleeding (no concentrations of aggregates) around the edges [EN12350-8, SCHU05, DEEB13].

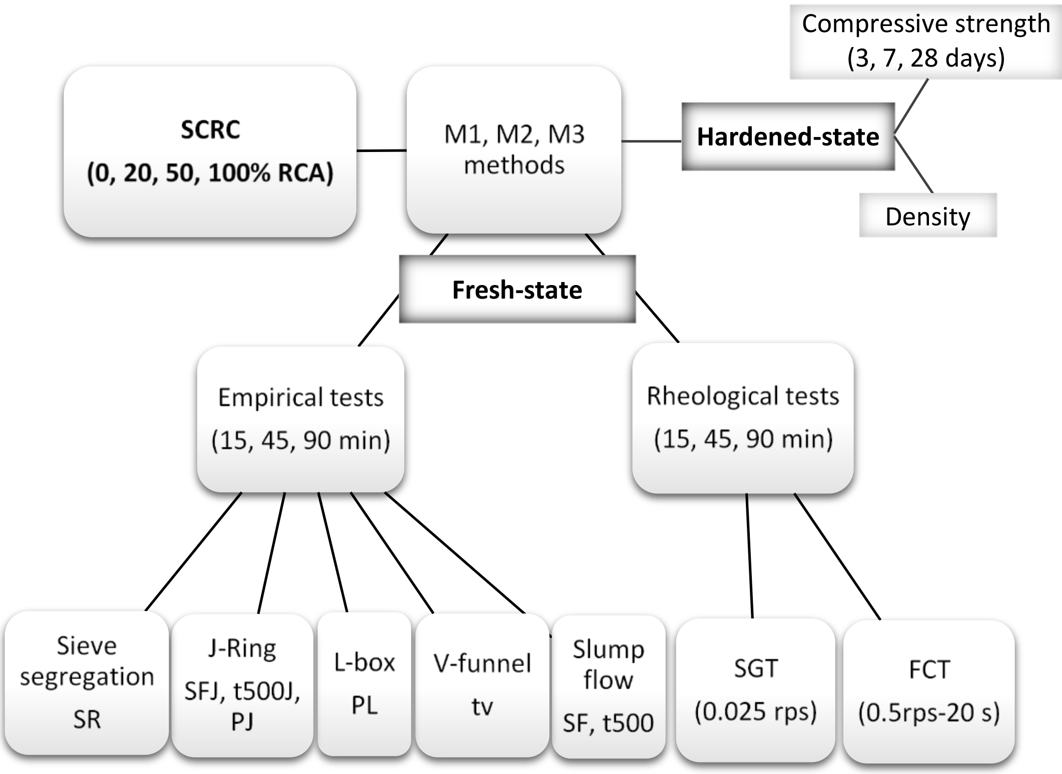


Figure III-33. Experimental program flow-chart (phases 1 and 2: Rheology and Robustness)

Because of its simplicity, the slump flow test can be done either on site or in the laboratory with an inverted or upright Abrams cone. The cone is placed on a non-absorbing levelled flat steel surface with a plane area of at least 900 mm x 900 mm. It is filled with SCC and lifted perpendicular to the base plate in a single movement. SCC flows out freely without obstruction from the cone. The stopwatch starts when the cone loses contact with the base plate and stops when the front of the concrete first touches the circle of 500 mm in diameter. The stopwatch reading is recorded as the t500 value. The test is completed when the concrete flow has ceased (Figure III-34). Then, two horizontal diameters (perpendicular to each other) are measured, the average of which being the slump flow [EN12350-8].

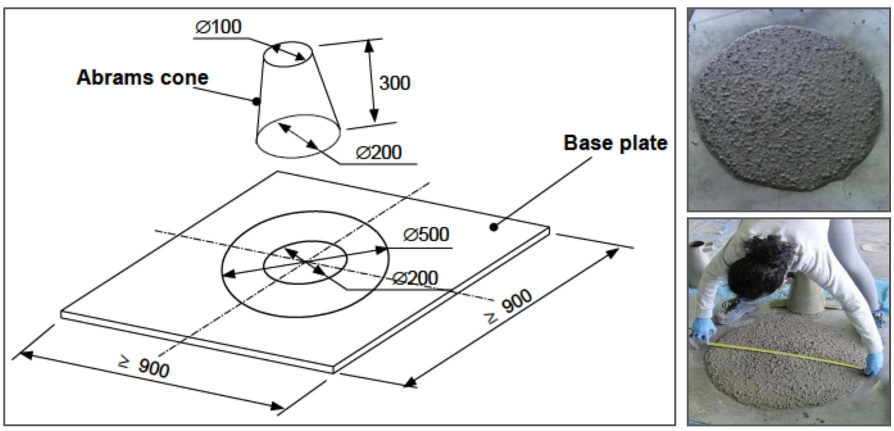


Figure III-34. Schematic of slump flow apparatus (left, [SCHU05]) and test (right)

Segregation can be detected by visually inspecting the periphery of the concrete after measuring the slump flow spread, and/or ensuring that no coarse aggregates have lifted in the centre of flow. The appearance of concrete can be qualitatively ranked, according to this visual examination method. Thus, the Visual Stability Index (VSI) procedure assigns a numerical rating of 0 to 3 according to the texture and homogeneity of the fresh mixture, based on observations made after conducting the slump flow test. However, this is a scarce method as it relies on the experience of the individual and fails to evaluate the segregation quantitatively.

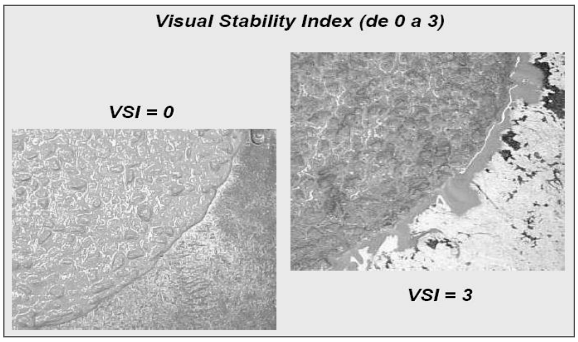


Figure III-35. Visual stability index

V-funnel test

As shown in Figure III-36, the V-funnel test consists of a V-shaped recipient with an opening of 65 x 75 mm at the bottom. At a given time after the recipient is filled, the bottom gate is removed and the time required for the concrete to flow through the tapered outlet is determined (tv) [EN12350-9]. This test is used to evaluate the ability of aggregate particles and mortar to change their flow paths and spread through a restricted section without segregation and blockage [KHAY08].

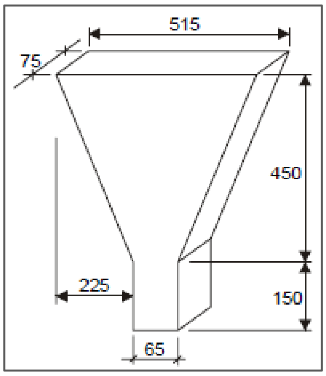


Figure III-36. Schematic of V-funnel apparatus (left, [SCHU05]) and test (right)

L-box test

The L-box test aims to investigate the passing ability of SCC. It measures the height reached by the fresh SCC after passing through the specified gaps of the steel bars and flowing within a defined flow distance. The passing or blocking behaviour of SCC can be estimated using the height reached [SCHU05].

After filling the vertical column of the L-box, the gate is lifted to allow SCC to flow into the horizontal part after passing through the rebar obstructions. Two measurements are taken, H_1 and H_2, the height of concrete at the beginning and end of the horizontal section, respectively (Figure III-37). The ratio H_2/H_1 represents the passing ability (PL) [EN12350-10].

In the L-box, a gap of 59 or 41 mm between 2 or 3 smooth steel bars of 12 mm in diameter respectively, can be used to represent light or dense reinforcement. The first option was used in this work.

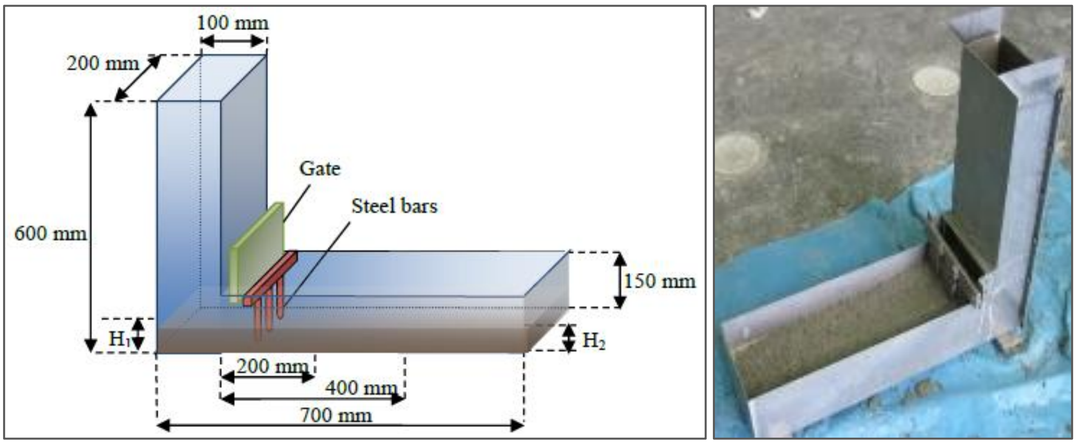


Figure III-37. Schematic of L-box apparatus (left, [DEEB13]) and test (right)

J-Ring test

The J-Ring test is used to assess the restricted deformability of SCC through closely-spaced obstacles [KHAY08]. It consists of an open steel ring, drilled vertically with holes to accept threaded sections of reinforcement bar. The diameter of the ring is 300 mm and the height 100 mm. The bars can be of different diameters and spaced at different intervals, although in accordance with normal reinforcement considerations, an appropriate space would be three times the maximum aggregate size. Two different gaps of 59 or 41 mm between 12 or 16 bars of 18 mm in diameter respectively can be used. A minor distance between bars simulates a denser reinforcement. The second option was used in this work.

The J-Ring test measures three parameters: flow spread, flow time and blocking step. The J-Ring flow spread (SFJ) indicates the restricted deformability of SCC due to the blocking effect of the reinforcement bars and the flow time (t500J) indicates the rate of deformation within a defined flow distance. The blocking step (PJ) quantifies the effect of blocking [SCHU05].

The ring is positioned on the base plate around the slump cone. This is filled with the sample from the bucket without any external compacting action. Then, the cone is lifted perpendicular to the base plate in a single movement, in such a manner that the concrete is allowed to flow out freely without obstruction from the cone [EN12350-12]. The stopwatch is started just at the moment the cone leaves the base plate and is stopped when the front of the concrete first touches the circle of 500 mm in diameter. This period is the J-Ring flow time (t500J). When the concrete flow has ceased, the largest diameter of the flow spread and that perpendicular are measured, and the mean diameter (SFJ) is determined (Figure III-38).

The difference in height of the concrete inside and outside of the J-Ring is also used to assess the passing ability of SCC and its resistance to blockage and segregation (PJ). This is carried out by measuring the Δh_0 value at the centre of the J-Ring and at four points outside the J-Ring, two (Δh_{x1}, Δh_{x2}) in the *x*-direction and the other two (Δh_{y1}, Δh_{y2}) in the *y*-direction (perpendicular to *x*) (Figure III-38). The J-Ring blocking step is calculated as follows (Eq. 1):

$$PJ = \frac{(\Delta h_{x1}+\Delta h_{x2}+\Delta h_{y1}+\Delta h_{y2})}{4} - \Delta h_0 \qquad (1)$$

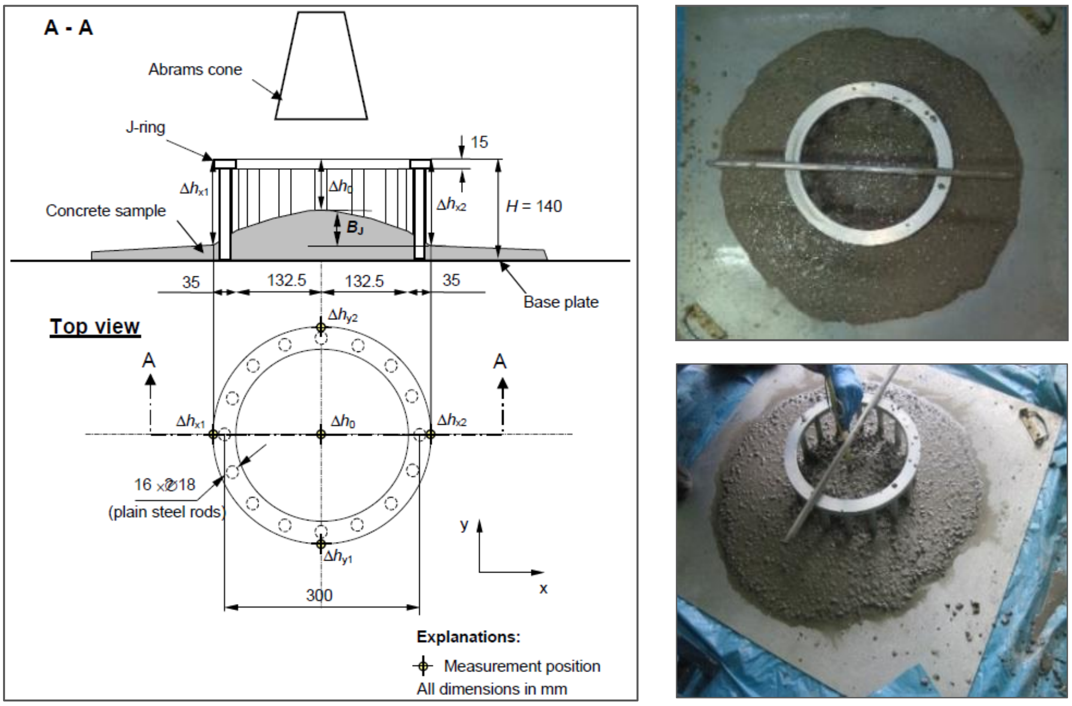


Figure III-38. Schematic of J-Ring apparatus (left) [SCHU05] and test (right)

Sieve segregation test

The sieve segregation test aims to investigate the resistance of SCC to segregation by measuring the portion of the fresh SCC sample passing through a 5 mm sieve [EN12350-11]. If the SCC has poor resistance to segregation, the paste or mortar can easily pass the sieve. Therefore, the sieved portion indicates whether or not the SCC is stable.

In this test, 10 L of fresh SCC is placed into a bucket and allowed to settle over a 15 min period. Then, a 4.8 ± 0.2 kg sample is poured onto the central part of the sieve from a height of 50 ± 5 cm. Two minutes after pouring, the sieve is gently removed without any shaking action (Figure III-39) and the mass percentage of the sample passing through the sieve is calculated (SR).

Figure III-39. Sieve segregation test

5.1.1.2 Rheological tests

The self-compacting concrete mixture is strongly dependent on the composition and characteristics of its constituents. The basic property influencing its fresh-state performance is its rheological behaviour. Understanding its rheological parameters, namely yield stress and plastic viscosity, provides a quantitative and fundamental way to describe SCC's filling ability, passing ability and resistance to segregation.

In this research, the rheological tests were conducted with an ICAR rheometer, which is a portable rheometer with vane geometry (Figure III-40). It is a rotational rheometer model where a four-bladed vane rotates with axial symmetry at a variable speed.

Figure III-40. ICAR rheometer [ICAR07]

The vane is 127 mm in height and diameter. The selection of the rheometer container size is based on the maximum aggregate size. The gaps between the vane and the edges of the concrete specimen should be at least 4 times the maximum aggregate size. This condition was well satisfied since the maximum size fraction used was a 4-11 mm and the container diameter was 305 mm. Moreover, the container features a series of vertical strips, which are provided to prevent slippage between the concrete and the container wall.

Two different tests were carried out with the ICAR rheometer: a stress growth test and a flow curve test. The stress growth test is used to determine the static (at rest) yield stress, while the flow curve test is used to measure the relationship between shear stress and shear rate (flow curve) which, once adjusted to a rheological model, allows the dynamic yield stress and plastic viscosity to be determined. The yield stress measured with the flow curve test is the dynamic yield stress because it is measured after the structural breakdown of the mix, thereby avoiding the effects of thixotropy.

The stress growth test involves rotating the vane at a low and constant speed (Figure III-41) while monitoring the build-up in torque (Figure III-42). The maximum torque corresponds to the static yield stress. This test is highly dependent on the shear history of the sample.

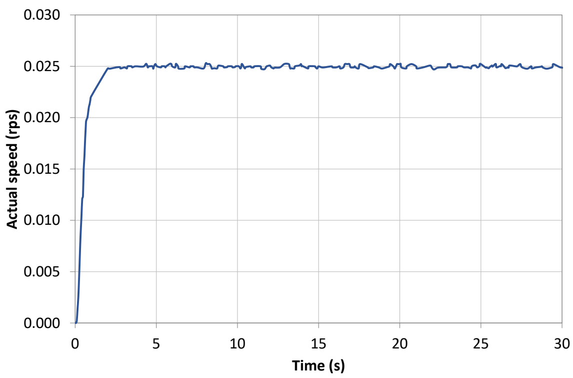


Figure III-41. Speed vs. Time. Stress growth test

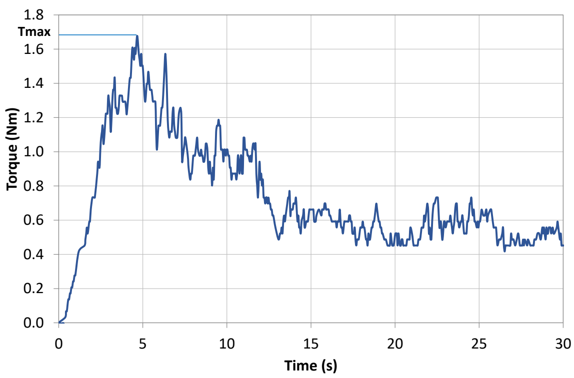


Figure III-42. Torque vs. Time. Stress growth test

When the stress growth test is carried out, the ICAR rheometer software automatically selects the maximum recorded torque (relative value). The yield stress (absolute value) is then calculated using with the following equation (Eq. 2):

$$\tau_0 = \frac{2T}{\pi D^3\left(\frac{h}{D}+\frac{1}{3}\right)} \qquad (2)$$

Where τ_0 is the yield stress, T is the maximum torque, D is the diameter of the vane and h is the height of the vane. In this equation, the shear stress is assumed to be evenly distributed on the side and ends of the vane.

The flow curve test (Figure III-43 and Figure III-44) consists of a breakdown, or pre-shear period, followed by a series of flow curve points. The purpose of the pre-shear period is to minimise the effects of thixotropy and provide a consistent shear history. It consists of a single, constant speed, typically equal to the maximum test speed. After this period, the flow curve is immediately started. A single test consists of a specified number of points in ascending or descending order (Figure III-45).

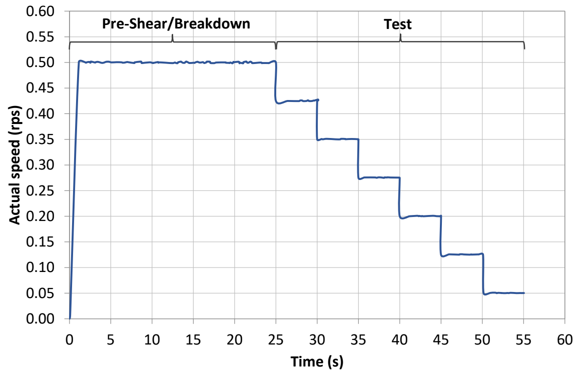


Figure III-43. Speed vs. Time. Flow curve test

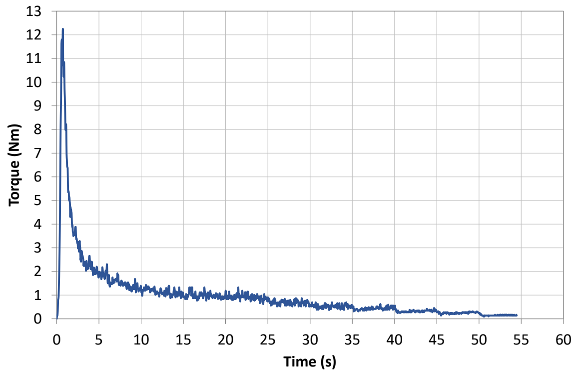


Figure III-44. Torque vs. Time. Flow curve test

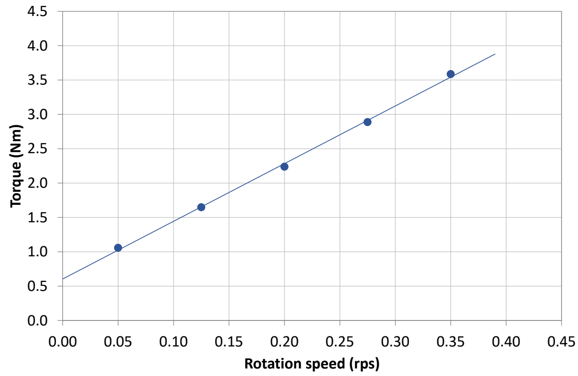


Figure III-45. Typical flow curve based on Bingham model on the 5 lowest points

The ICAR rheometer software performs all necessary functions: it controls the rheometer, records test data, computes test results and stores data. The entire software program is operated from a single screen which is split into three rows: the top row consists of general inputs, the second row of test-specific inputs (Figure III-46), and the third row provides messages.

In this work, the stress growth test started as soon as the rheometer vane was immersed into the concrete. The vane was rotated at a low and constant speed (0.025 rps) and the torque value was monitored on the computer screen. Once the peak torque was reached, the vane was removed and the concrete was remixed with a shovel. Then, the vane was reinserted into the concrete and the flow curve test started. In this second test, after a period of 20 s at a constant speed of 0.50 rps, the torques at decreasing speeds (from 0.5 to 0.05 rps in seven steps) were measured.

At the end, the vane was removed and concrete was again remixed with a shovel and left to rest. Unlike the case of workability tests, the concrete sample used for rheological properties was kept at rest in the rheometer container without any agitation.

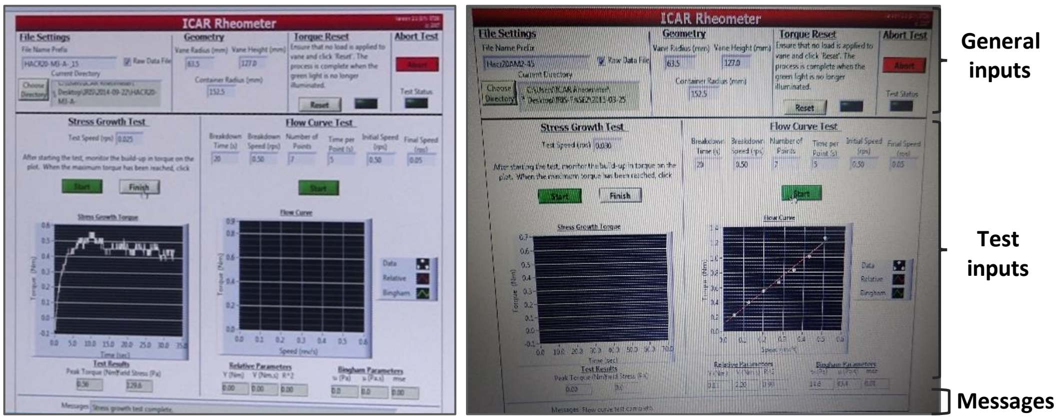


Figure III-46. Screen of a stress growth test (left) and of a flow curve test (right)

These rheological tests (Figure III-47) were performed at 15, 45 and 90 min from the moment of cement-water contact (mix age), which corresponds to 5, 30 and 45 min resting time respectively.

Figure III-47. Rheological test

5.1.2 Hardened-state tests

In both working phases, density of fresh and hardened concrete and compressive strength were determined for each mix.

Density of fresh concrete was obtained according to EN 12350-6 [EN12350-6]. Moreover, density of hardened concrete was evaluated one day after the concrete cubes were demoulded according to EN 12390-7 [EN12390-7]. To do so, nine 100 x 100 x 100 mm cube specimens were used (Figure III-48).

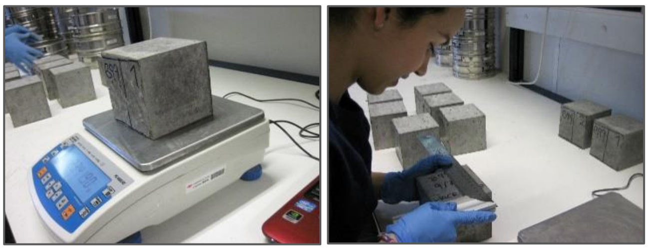


Figure III-48. Density of hardened concrete

Compressive strength tests were carried out according to EN 12390-3 [EN12390-3] using nine cube specimens of 100 x 100 x 100 mm in size which were tested at different ages (3, 7 and 28 days). All concrete cubes were demoulded after 24 hours casting and placed in a curing chamber until the testing age. Then, the cubes were tested perpendicular to the casting direction. The compression machine exerted a constant progressing load until failure, with a loading rate of 0.6 ± 0.2 MPa/s ($N/mm^2 \cdot s$) (Figure III-49).

Figure III-49. Compressive strength test

5.1.3 Rheology and Robustness testing protocol

As aforementioned, to assess rheology and robustness, a series of tests were carried out at 15, 45 and 90 min after cement-water contact. Each series took no more than 5 min and consisted of various empirical and rheological tests (Figure III-50).

Figure III-50. Different test devices

Four operators carried out the tests in order to shorten the testing time and minimise errors. The testing procedure was as follows:

1. After the mixing process, the concrete was poured from the mixer into the rheometer container and several buckets. One of the buckets was covered to perform the sieve segregation test later on.
2. At each testing age, two operators carried out the L-box test while another carried out the V-funnel test. Before beginning each empirical test, the concrete from the buckets was remixed with a shovel.

3. At the same time, the fourth operator started the rheological tests from the concrete being at rest:
   3.1. The stress growth test started as soon as the vane was immersed into the concrete. The vane was rotated at a low and constant speed of 0.025 rps and the torque value was monitored on the computer screen.
   3.2. Once the peak torque was reached, the vane was removed and the concrete was remixed with a shovel.
   3.3. The vane was reinserted into the concrete and the flow curve test started. After a period of 20 s at a constant speed of 0.5 rps, the torques at decreasing speeds were measured.
   3.4. At the end, the vane was removed and the concrete was again remixed with a shovel and left to rest until the next testing time.
4. Once the L-box was finished, its two operators carried out the slump flow and J-Ring tests. Again in this case, before these empirical tests, concrete was remixed with a shovel. At the same time, the V-funnel test was also finished and then its operator filled the nine cubic (10 x 10 x 10 cm) specimens necessary to carry out the compressive strength test. In the meantime, the fourth operator was finishing the rheometer tests.
5. The concrete used in these empirical tests was put back into the mixer, and two minutes and a half before the next testing time (45 min and 90 min), it was remixed for 30 s and poured into the buckets again. The concrete sample used in the rheological tests was left to rest in the rheometer container without any agitation.

Finally, two operators carried out the sieve segregation test, which was carried out after the resting period of 15 min established by its corresponding standard. The concrete used in this test was discarded.

5.2 Phase 3: Thixotropy

The main objective of this sub-section is to present the testing methods and protocols adopted to quantify the thixotropy and how this property influences the interlayer bond strength of SCRC.

The experimental program of this final working phase is summarised in Figure III-51.

5.2.1 Assessment of SCRC thixotropy

There are no standard methods to measure thixotropy, but typical thixotropic experiments often consist of either rheological tests conducted at a constant shear rate (equilibrium flow curves) or at varied shear rates (hysteresis curves) [KHAY08].

In this research three different methods were used:

- Structural breakdown curves at various rotational speeds (steady state approach).
- Hysteresis loop flow curves.
- Yield stress at rest (also referred to as static yield stress and shear-growth yield stress).

Then, the first objective of this third working phase is to describe these three methods to evaluate the degree of thixotropy of SCRC mixes.

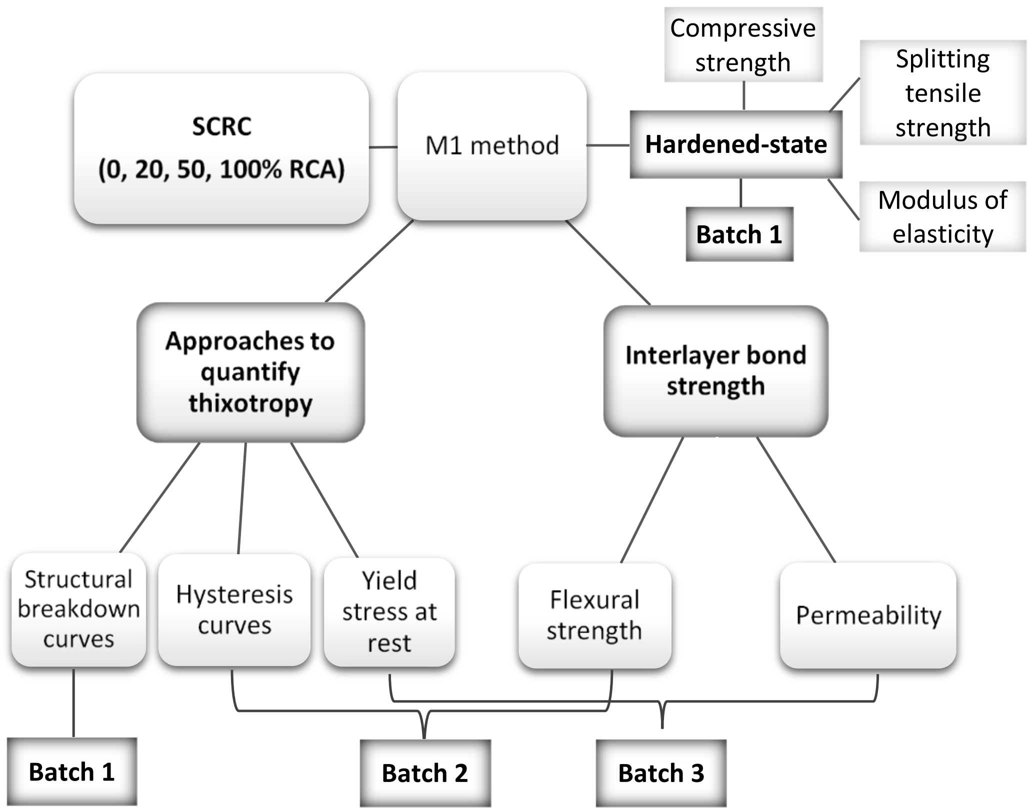


Figure III-51. Experimental program flow-chart (phase 3: Thixotropy)

Structural breakdown curves

The concrete is subjected to different constant rotational speeds of 0.3, 0.5, 0.7 and 0.9 rps. In this protocol [ASSA04], immediately after the vane drive mechanism is started, torque readings are noted according to time (Figure III-52).

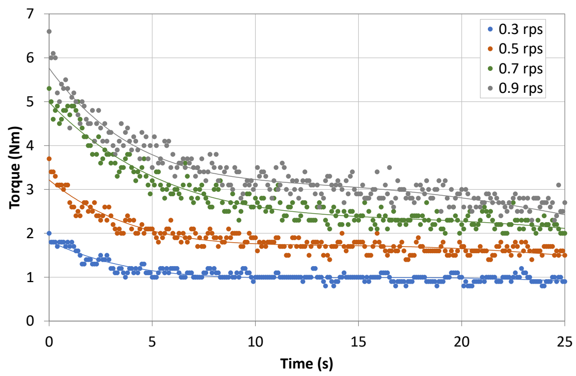


Figure III-52. Example of structural breakdown curves

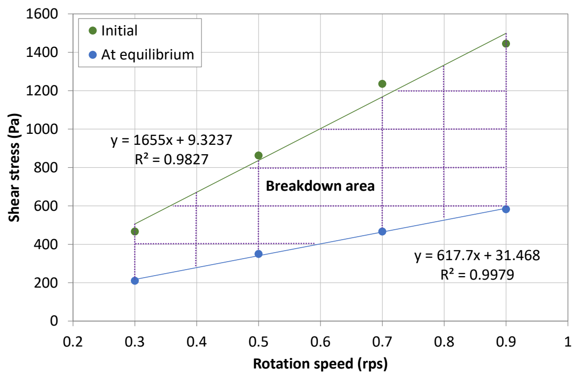


Figure III-53. Example of structural breakdown area calculation

The first reading is considered the initial maximum torque value necessary to initiate the flow of the vane. This initial maximum torque is used to calculate the peak yield stress, which corresponds to the initial structural condition. The average of the five smallest measurements over the 25 s duration at each rotational speed, is taken as the equilibrium torque value. The equilibrium torque is used to calculate the shear stress at equilibrium, which corresponds to an equilibrium condition that is independent of the shear history, for that speed. The rest period established between each of the four structural breakdown tests was 5 min. During this period the concrete was not subjected to any shearing action. It should be noted that after each test the concrete in the rheometer bowl was rehomogenized and then left to rest.

The difference between the peak yield stress and the shear stress at equilibrium, for a given rotational speed, gives a measurement of the amplitude of the structural modifications inside the tested material. A greater difference between shear stress initially and at equilibrium implies a higher degree of thixotropy.

The enclosed area between the initial flow curve and the equilibrium flow curve can be used to quantify the thixotropic phenomenon. This area, known as the "breakdown area" (Figure III-53), provides a measurement of the energy required per unit time and unit volume of concrete necessary to break the initial linkages and internal friction, in order to pass from the initial state into a state of equilibrium [KHAY07].

Two rotational rheometers with a four-bladed vane were used (Figure III-54): the one used in “Rheology“ and “Robustness” phases was limited to speeds no higher than 0.5 rps, as well as one capable of working at high rotational speeds (0.7 and 0.9 rps).

Figure III-54. Rheometers used

Hysteresis loop flow curves

When shear stress is plotted as a function of shear rate, the up (loading) and down (unloading) curves can be obtained (Figure III-55).

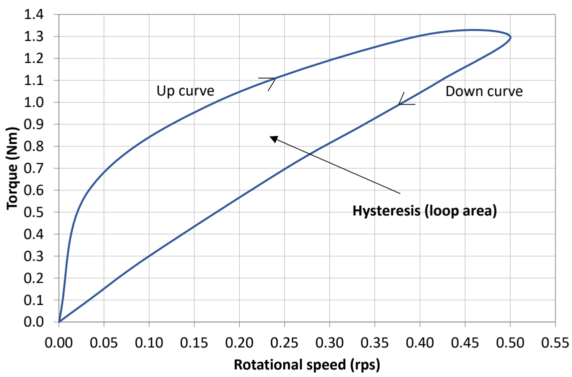


Figure III-55. Example of a hysteresis loop flow curve

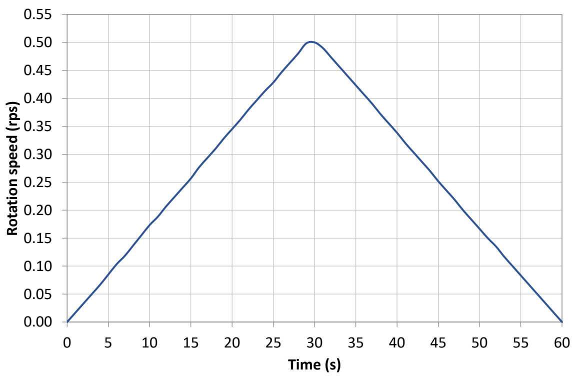


Figure III-56. Rotation speed vs. Time on a hysteresis loop flow curve test

The enclosed area between the up and down curves (i.e. hysteresis) provides a measure of the degree of thixotropy in the sample [KHAY07]. A greater area implies a higher degree of thixotropy.

In this test, the material was sheared with a continuously increasing shear rate and continuously down again to zero shear rate (Figure III-56). The rotational speed was applied for 60 s from zero to 0.5 rps and then from 0.5 rps to zero.

Yield stress at rest

The yield stress can be used as a measure of the strength and number of interparticle bonds that are ruptured due to the applied shear or stress [KHAY07]. The protocol adopted for the determination of yield stress at rest (also referred to as static yield stress and shear-growth yield stress) consisted of applying a minute and constant rotational speed to a vane immersed in the fresh material and recording the resulting torque as a function of time. The speed was set at 0.03 rps (Figure III-57). This was chosen so that the maximum torque is not affected by the rotational speed of the vane.

The profile shows a linear elastic region, followed by a yielding moment where the torque exerted on the vane shaft reaches a maximum value, corresponding to the beginning of the microscopic destruction of the bonds between the particles and the suspension allowing the material to flow. Beyond this value, the torque decays towards a steady state region. Therefore, the peak shear stress value is considered as the yield stress at rest (Figure III-58). A greater difference between static (at rest) and dynamic yield stress implies a higher degree of thixotropy.

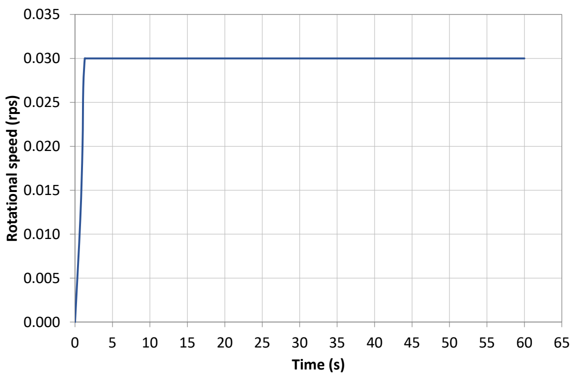


Figure III-57. Typical speed-time profile of yield stress at rest test

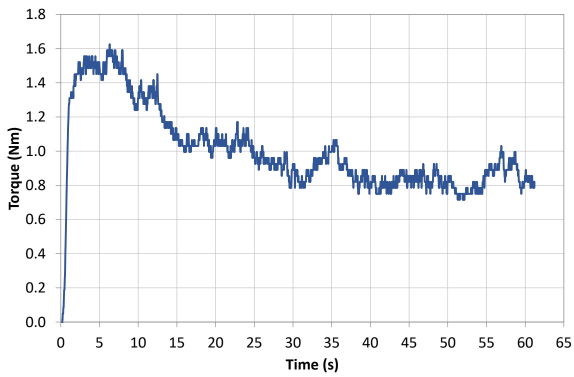


Figure III-58. Typical torque-time profile of yield stress at rest test

The presence of such maximum torque response is an index of thixotropy that can be explained by the concept of structural deformation and breakdown of the bond in the flocculated system. The maximum value during this profile corresponds to the yield shear stress at rest. Its calculation from the measured maximum torque requires knowledge of the geometry of the yield surface and shear stress distribution on the surface of the device.

5.2.2 Interlayer bond strength of SCRC

During placing, a layer of thixotropic SCC has a short time to rest and build structure, before a second layer of concrete is cast over it. If it builds structure too much and its apparent yield stress increases above a critical value, then the two layers do not mix at all and, as vibrating is forbidden in the case of SCC, a weak interface between the concrete layers may appear in the final structure. The first consequence is often only visual, but losses of mechanical strength have also been reported. Moreover, it can be expected that this weak interface may locally increase the porosity and thus permeability to aggressive substances [ROUS08].

In this way, the second objective of the third working phase is to evaluate the effect of structural build-up at rest on bond strength and water permeability that can be developed between SCRC layers following a certain period of rest. This is related to the assessment of thixotropy as it can provide some indication of the degree of SCRC structural build-up.

Thus, in this research, two methods were used to assess the influence of thixotropy on interlayer bond strength of SCRC: 1) interlayer bond strength using flexure tests; 2) interlayer bond strength using water permeability tests.

The bond strength and water permeability were measured with various delay times between layers from 0 to 60 min (Table III-10) taking into account the time since the cement-water contact in mixing (the reference time).

Table III-10. Cement-water contact vs. Delay time between layers

Time since cement-water contact	Delay time between successive layers
15 min	0 min
30 min	15 min
45 min	30 min
75 min	60 min

Interlayer bond strength using flexure tests

In this method, small beams with dimensions of 100 mm in width and height and 600 mm in length were cast (Figure III-59). Small notches were formed during casting at mid-length point to ensure that the failure takes place at mid-span.

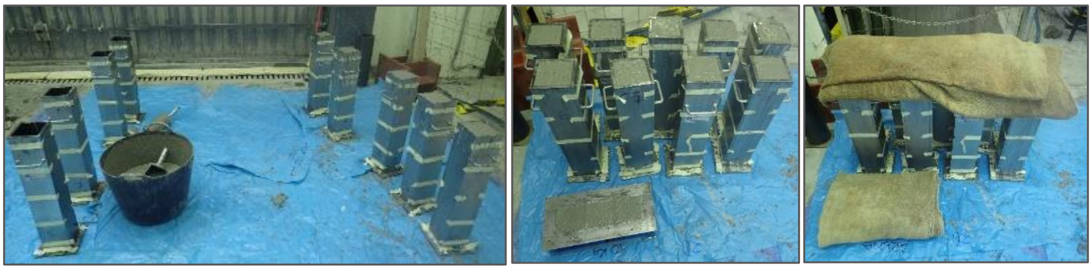


Figure III-59. Casting and curing of small beams for bond strength under flexure

For each type of concrete, 2 reference beams were cast in one layer, and 7 beams were cast in two layers considering the interface between layers at mid-span. As aforementioned, the delay time between casting the first and the second layer was 0, 15, 30 and 60 min (Figure III-60).

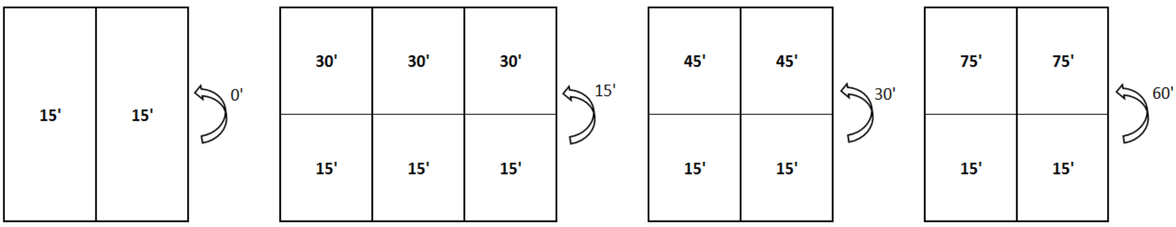


Figure III-60. Schematic of flexural test beams

Each prismatic specimen was subjected to a three-point bending test (Figure III-61). The beam was placed on two supports and the actuator applied a force in the exact middle of the two supports. Immediately before failure, the machine recorded a force and a deformation. The maximum flexural strength of the specimen was determined.

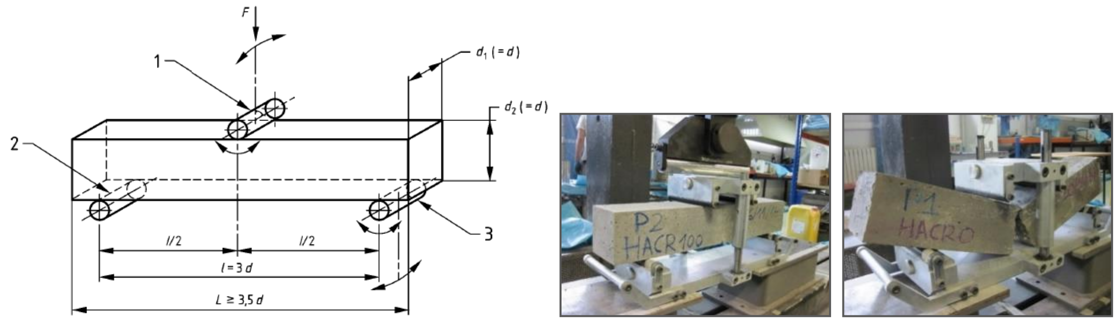


Figure III-61. Schematic of flexural test geometry (left) and test (right)

Interlayer bond strength using water permeability tests

For dense and, hence, low permeability concrete, the depth of penetration method is usually a more practical proposition than permeability flow tests. The procedure is to apply water under pressure to one surface of the specimen for a specific time and then to split the specimen perpendicular to the injected face and visually determine the penetration depth.

Then, in this second method, prismatic specimens with dimensions of 100 mm in width and height and 200 mm in length were cast. Small notches were formed during casting at mid-length point. In this case, for each type of concrete, 2 reference specimens were cast in one layer, and 4 specimens were cast in two layers. The delay time between casting the first and the second layer was 0, 15 and 60 min (Figure III-62). Two specimens were considered for each delay time.

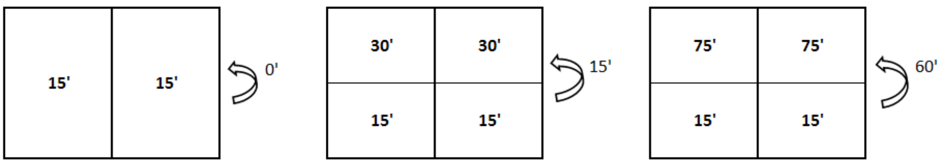


Figure III-62. Schematic of permeability test prismatic specimens

The test was carried out according to European Standard EN 12390-8 [EN12390-8] at an age of 28 days. The test cell assembly used had the provision for testing six specimens at a time (Figure III-63).

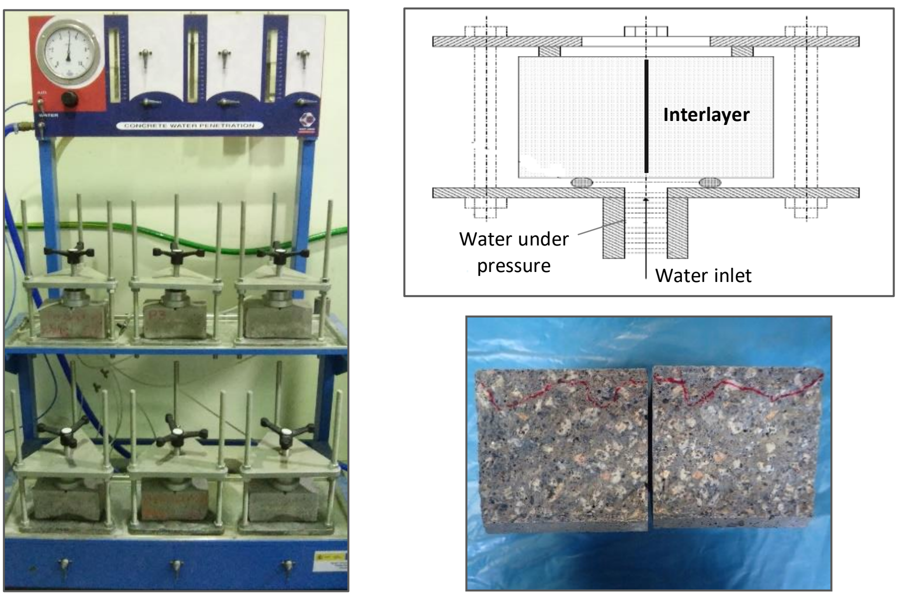


Figure III-63. Testing protocol for water penetration under pressure

Once they were assembled in the test cells, a water pressure of 500 kPa (5 bar) was applied for 72 hours. Water pressure was applied by means of an arrangement consisting of a water tank connected to an air compressor through a valve, used to adjust the pressure (Figure III-63).

Finally, each specimen was subjected to a three-point bending test considering the vertical interface between layers at mid-span (Figure III-64). Once it was divided into two parts, the water penetration depth was defined as illustrated in Figure III-63.

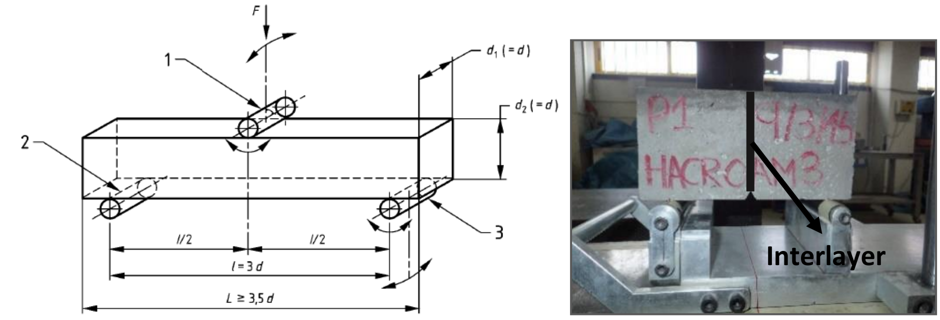


Figure III-64. Schematic of three-point bending test geometry (left) and test (right)

5.2.3 Hardened-state tests

In the "Thixotropy" working phase, the testing programme to determine the basic mechanical properties included the following tests: compressive strength, modulus of elasticity and splitting tensile strength (Figure III-65).

Three cylindrical specimens of 150 x 300 mm were made to determine the compressive strength (EN 12390-3) [EN12390-3]. They were all tested at 28 days. The modulus of elasticity and the splitting tensile strength were also measured at 28 days, and each property was measured with three cylindrical specimens of 150 x 300 mm, using EN 12390-13 and EN 12390-6 standards respectively [EN12390-13, EN12390-6].

Four strain gauges were fitted over the specimens used in the modulus of elasticity tests. Two were used to measure axial strain and the other two were used to measure transverse strain. Thus, throughout these tests, loads and strains were measured, making it possible to define the stress–strain curves under the controlled load rate up to the maximum stress and for the elastic branch.

Figure III-65. Compressive strength, modulus of elasticity and splitting tensile strength

5.2.4 Thixotropy testing protocol

In this third phase, three batches for each type of concrete (0%, 20%, 50% and 100% of RCA) were created. The first batch was used to carry out the four structural breakdown tests and the specimens were made to evaluate compressive strength, modulus of elasticity and splitting tensile strength.

With the second batch, the hysteresis loop test was conducted and the specimens to carry out bond strength under flexure were made. With the third batch, the protocol adopted for the determination of yield stress at rest was executed and the specimens to develop water permeability tests were fabricated.

Batch 1

Once the concrete was mixed according to the mixing protocol described in previous sections, the testing protocol was that developed to measure the structural breakdown curves. The protocol for each rotational speed (0.3, 0.5, 0.7 and 0.9 rps) was the same. This protocol was developed with four operators: the rheological tests were carried out by two of them and the slump flow test by the other two.

In this case, the testing protocol was as follows:

1. The rheometer container and several buckets were filled with concrete.
2. Two operators performed the slump flow test at the same time as the rheological tests. Before this empirical test, concrete was remixed with a shovel in the bucket.
3. The rheological tests at each speed were carried out as follows:
    a. The concrete was left to rest for 5 min in the rheometer.
    b. The vane was immersed into the concrete and the rotational speed was applied. It was maintained for 25 s (time enough to measure the maximum torque).
    c. The vane was removed, concrete remixed with a shovel and left to rest for 5 min.
    d. Then, the vane was reinserted into the concrete and the same protocol was repeated with the corresponding speed.
4. When the slump flow test was finished, its two operators filled the nine cylindrical specimens (150 x 300 mm) necessary to develop the compressive strength, modulus of elasticity and splitting tensile strength tests.

Batch 2

In this case, the testing protocol was as follows:

1. The rheometer container and several buckets were filled with concrete.
2. At 15 minutes, two operators filled the small beams for flexure tests. They filled all specimens until mid-length except those without delay time between layers that were filled completely.
3. At the same time as each of the rheological tests, the corresponding small beams were filled completely. Concrete from buckets was remixed with a shovel for 30 s before casting the second layer.
4. Also at the same time as each of the rheological tests, two operators performed the slump flow test. Before this empirical test, concrete was remixed with a shovel in the bucket.
5. The rheological test at each time (15, 30, 45 and 75 min) was made as follows:
    a. The concrete was left to rest in the rheometer.
    b. The vane was immersed into the concrete and the rotational speed was applied according to the hysteresis loop protocol (for 60 s, from zero to 0.5 rps and then from 0.5 rps to zero).
    c. The vane was removed, concrete remixed with a shovel and left to rest until the next testing time.

d. At the following time, the vane was reinserted into concrete and the same protocol was repeated.

Batch 3

Finally, with the third batch, the testing protocol was as follows:

1. The rheometer container and several buckets were filled with concrete.
2. At 15 minutes, two operators filled the prismatic specimens for permeability tests. They filled all specimens until mid-length except those without delay time between layers which were filled completely.
3. At the same time as each of the rheological tests, the corresponding specimens were filled completely. Concrete from buckets was remixed with a shovel for 30 s before casting the second layer.
4. Also at the same time as each of the rheological tests, two operators performed the slump flow test. Before this empirical test, concrete was remixed with a shovel in the bucket.
5. The rheological test at each time (15, 30, 45 and 75 min) was made as follows by one operator:
    a. The concrete was left to rest in the rheometer.
    b. The vane was immersed into the concrete and the rotational speed was applied according to the yield stress at rest protocol. It was a low and constant rotational speed of 0.03 rps for 60 s (time enough to measure the maximum torque and to reach the steady state region).
    c. The vane was removed, concrete remixed with a shovel and left to rest until the next testing time.
    d. At the following time, the vane was reinserted into concrete and the same protocol was repeated.

CHAPTER IV
Hardened-state behaviour of recycled concrete and self-compacting recycled concrete using database analysis

1 INTRODUCTION AND OBJECTIVES

Recycled concrete use has increasingly developed in recent years supported by vast scientific experience. A significant number of research papers have been published regarding the mechanical properties of recycled concrete, which has reduced the uncertainty related to its performance. Therefore, it is easy to create a database that includes these published results in order to draw general conclusions regarding recycled concrete (RC).

On the other hand, many studies deal with hardened properties of self-compacting concrete (SCC), comparing them with those of its equivalent vibrated concrete. Regarding this subject, some authors indicate that changes in mixture design and fluidity of SCC can influence its hardened properties, which may cause it to diverge from what is commonly expected from vibrated concrete of normal consistency [KHAY08]. However, most studies state that if SCC is well designed, it can provide similar mechanical properties to its equivalent vibrated concrete [DOMO07].

Therefore, considering this hypothesis, self-compacting recycled concrete (SCRC) is expected to present properties in hardened-state similar to those of its equivalent vibrated recycled concrete. Hence, it is then possible to study hardened-state behaviour of SCRC by analysing that of vibrated recycled concrete with which there is more extensive experience.

Firstly this chapter focuses on the prediction of some of the most important properties of structural vibrated recycled concrete (compressive strength, modulus of elasticity and splitting tensile strength) taking into account, not only the recycled percentage and the quality of the recycled aggregates used, but also the production method.

Finally, in the last section, the results obtained with vibrated recycled concrete are used to predict self-compacting recycled concrete behaviour and this is followed by an analysis of the accuracy of these predictions when SCRC is used.

2 RECYCLED CONCRETE (RC)

The greatest difference between a recycled aggregate and a conventional aggregate is the adhered mortar of the original concrete. This is the cause of the main differences between the physical properties of recycled aggregates and conventional aggregates, where the higher absorption of recycled aggregates (which influences fresh concrete properties, particularly its workability) should be noted. Both this and the moisture state, affect the effective water to cement ratio which finally influences the properties of fresh and hardened concrete [EVAN10, PADM09].

When recycled concrete is used, the authors propose three production methods to compensate the high water absorption of recycled aggregates. In the first method, aggregates are added after being immersed in water for a pre-established time (*pre-soaking*), generally 10 min [ZHAN07, RÜHL92, AKBA11, NEAL98]. In the second, aggregates are added with their natural moisture, compensating the aggregate absorption by adding extra water (*extra water*), generally the water necessary to reach 80% saturation. Lastly, other authors produce concrete without taking into account the high absorption of the recycled aggregate (*dry*), and control workability with supplementary quantities of superplasticiser.

Therefore, essentially, three alternatives have been proposed [references 1-81, Chapter X, section “References – Recycled concrete database”]: a) to pre-soak the recycled aggregates (*pre-soaked-PS*) for a fixed time, b) to work with air-dry aggregates increasing the amount of water incorporated in the mix according to a fixed percentage of the saturated surface dry state (*air-dry with extra-water-ADwEW*), or c) to work with air-dry aggregates without any extra water but using a significant amount of superplasticiser to maintain workability (*air-dry without extra-water-AD*).

It is obvious that the selected production method (i.e. the mixing procedure) influences the recycled concrete properties. In fact, recycled concrete presents two ITZ (interfacial transition zones), one located between the original aggregate and the old adhered mortar and the other between said adhered mortar and the new mortar matrix [OTSU03] (Figure IV-1). The strength of this concrete is normally influenced by the weakest one. It is agreed that the selected production method modifies the ITZ quality between the recycled coarse aggregate and the new paste [FERR11].

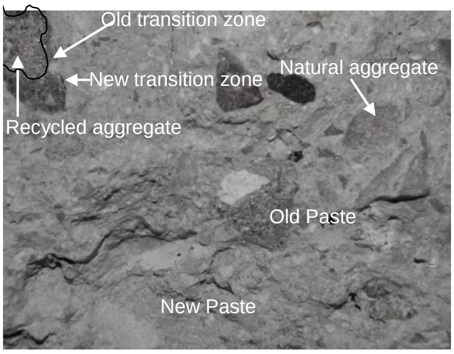


Figure IV-1. The recycled concrete *interfacial transition zones* (ITZ) [OTSU03]

In general terms, authors conclude that pre-saturated recycled aggregates cause damage in the ITZ between the recycled coarse aggregate and the new cement paste [ETXE07b], which has a negative effect on the concrete compressive strength [PELU09, GONZ11b, BARR97]. In the case of using recycled aggregates in the saturated surface dry state, the high water content inside the aggregate particles may result in bleeding. The water inside recycled aggregate particles can move to the cement paste, creating a relatively high water to cement ratio sited in the proximity of the particles. This process may weaken the link between the recycled aggregate and the cement matrix. Consequently, a high degree of bleeding leads to a lower recycled concrete strength [POON07].

Current trends suggest that the ADwEW method prevents the bleeding effect and hence, leads to better behaviour than the PS method [PELU09]. Lastly, the AD method avoids, in general, the damage to the ITZ although, nowadays, this method has almost been given up because very high superplasticiser quantities are required to maintain workability and, in some cases, it may be impossible to achieve.

Lastly, some authors have confirmed that the moisture state of recycled aggregates also introduces changes in the behaviour of recycled concrete [PELU09, POON04b, FERR11, CORI10b]. According to Poon et al. [POON04b], the initial slump of recycled concrete is strongly dependent on the initial free water content.

Regarding all of the aforementioned, the production method must be considered when analysing any property of recycled concrete. Hence, in this work, the main objective is to predict the basic mechanical properties of structural recycled concrete taking into account, not only the recycled percentage and quality of the recycled aggregates used, but also the production method. Furthermore, this prediction must conclude with the proposal of simple expressions which allow engineers to estimate properties of recycled concrete similarly to how those of conventional concrete are estimated.

2.1 Objectives

The first part of the study focuses on the influence of the recycled concrete production method, and recycled coarse aggregate quantity and quality, on some of the most significant properties of recycled concrete (compressive strength, modulus of elasticity and splitting tensile strength). To achieve this objective, a database has been developed [references 1-81, Chapter X, section "References – Recycled concrete database"] with 1831 mixes of 81 papers selected from over 250 international references related to the field of recycled concrete.

The database was developed considering works where the recycled coarse aggregate used was obtained from concrete waste (recycled concrete coarse aggregate). In this regard, all recycled coarse aggregates have presented a water absorption capacity under 8.5%. Furthermore, as different mechanical properties are achieved as a function of the method used to compensate the high water absorption capacity of recycled aggregates, the works have been classified considering the mixing procedure (PS, ADwEW and AD).

The properties studied are as follows: compressive strength, modulus of elasticity and splitting tensile strength. In the first case, this study focuses on comparing the compressive strength of conventional concrete with that of recycled concrete. The objective is to discover how much this property can decrease when recycled concrete coarse aggregates are used, by analysing different incorporation ratios and mixing procedures. The works used to develop this analysis have to use a control concrete (conventional concrete) and different recycled concretes made with the same dosage and materials except for the coarse aggregate, which will be replaced with recycled concrete coarse aggregate (by volume) at different percentages.

Regarding the modulus of elasticity and splitting tensile strength, there are three objectives: firstly, to compare these properties with those of conventional concrete. The only goal of this method is to obtain information, as this way of analysing the properties of recycled concrete is not useful for predicting them as a conventional concrete reference is needed. The second objective is to analyse whether or not it is necessary to adapt the prediction code expressions (adjusted for conventional concretes) to take into account the use of recycled aggregates, developing, if finally necessary, correction coefficients that allow engineers to predict recycled properties with the same approximation degree as with conventional concretes. These correction coefficients have been adjusted using multivariable regression. Lastly, the third objective is to optimize specific expressions to predict these properties in structural recycled concretes. Two different tools have been used to develop the expressions: multivariable regression and genetic programming. Both the correction coefficients and the new specific expressions must take into account the recycled concrete compressive strength, production procedure, replacement ratio and recycled concrete coarse aggregate quality.

The proposed expressions and also the correction coefficients have been analysed using different statistical indexes: the Pearson correlation coefficient (*r*), the mean squared error (MSE), the coefficient of variation (COV) and the mean average error (MAE). Regarding the proposed expressions, the statistical parameters have been compared with those obtained using expressions proposed by other authors. In this regard, and lastly, the best prediction expressions for the modulus of elasticity and the splitting tensile strength of structural recycled concretes have been proposed.

2.2 Methodology

2.2.1 Genetic programming methodology

Genetic programming (GP) is a subset of solution search techniques based on evolutionary computation. In GP, an analogy between the solution set to a problem and the individual set in a natural population is established, codifying the information of each solution using a tree-shaped structure. In this codification two types of nodes are differentiated. The first type are *non-terminal* nodes or *functions* where the algorithm operators are lodged (for example addition, subtraction, etc.). They are characterized as always having one or more children. The second type are *terminal* nodes or tree leaves, where the constant values and the previously defined variables are located. These nodes have no children [PERE12].

The most extensive GP application is probably to develop mathematical expressions. Its codifying manner enables them to be easily represented and they have been applied in many different engineering related fields [PERE10]. The results that were found have been very beneficial and, on a great number of occasions, the expressions achieved were an improvement on previously existing ones [CLAD14].

In this work, the algorithm developed is based on classic genetic programming techniques and has been specialized in the optimization of mathematical formulas (Figure IV-2). Therefore, the algorithm development has been focused on the symbolic regression technique for learning patterns. Furthermore, a module has been added to enable the incorporation of expert knowledge and to orientate the search process.

The first step involved debugging the database. It may seem trivial but it is essential to obtaining coherent and unbiased results. Having a complete and well verified database is an essential condition for the process. Refinement was carried out until a representative set was achieved. Once a good dataset had been obtained, this was divided into two subsets to see whether the results were correctly generalized: one for training and the other for testing (Figure IV-3).

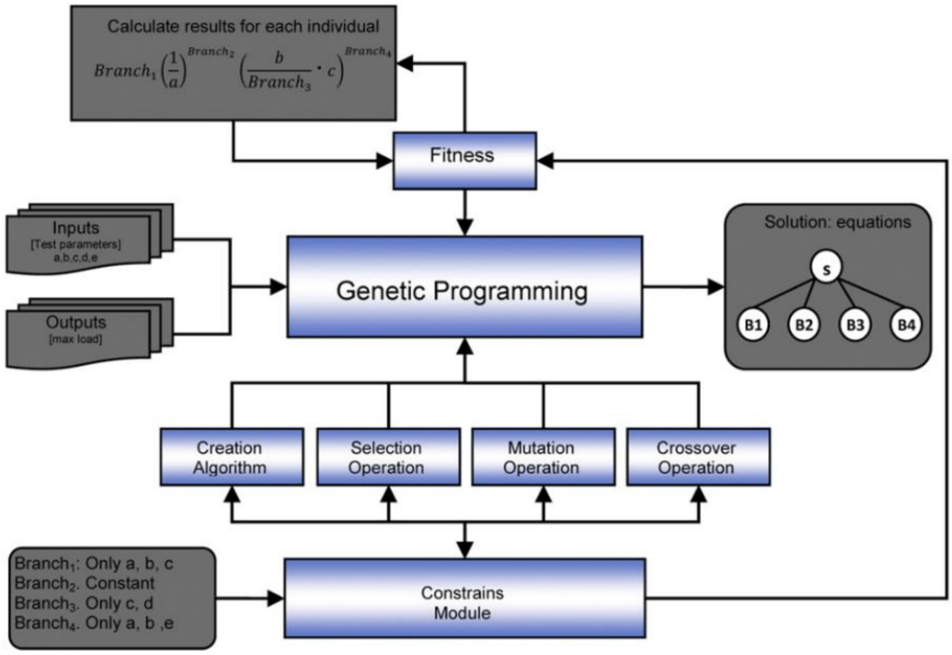


Figure IV-2. Algorithm example [PERE12]

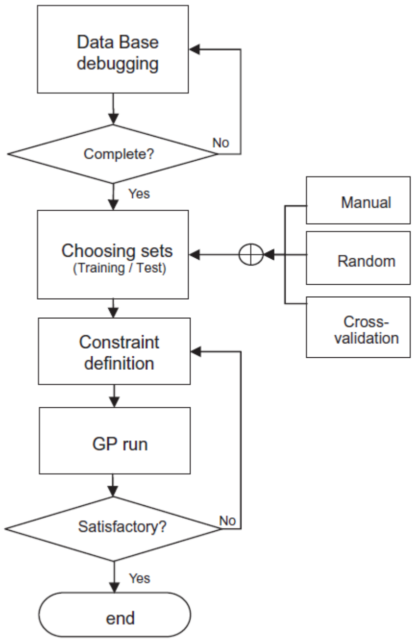


Figure IV-3. Methodology used [PERE12]

Definition of the initial equation was important in guiding the new expression search process. From this moment, an iterative process began, consisting of the definition of restrictions, execution and results analysis.

2.2.2 Conventional concrete property vs recycled concrete property

As mentioned, the first objective is to compare the conventional concrete property with that of recycled concrete. The aim is to discover how much one property can decrease when recycled concrete coarse aggregates are used, by analysing different incorporation ratios and mixing procedures, which have not been considered by other authors when developing their expressions but have a well-known influence on the properties of recycled concrete [CORI10a, GONZ11b, SEAR14, SILV15a].

To develop this kind of analysis, some works were selected from the database: those that use a control concrete (conventional concrete) and different recycled concretes made with the same dosage and materials except for the coarse aggregate, which will be replaced with recycled concrete coarse aggregate (by volume) at different percentages.

With these works, and using **linear regression**, a coefficient can be adjusted which allows the estimation of the recycled concrete property as a function of that of conventional concrete (Eq. 1). This coefficient will take into account the recycled content and the mixing procedure used.

$$Pro_{c,RC} = X(\%RCA) \cdot Pro_{c,CC} \quad (1)$$

Where:

$Pro_{c,RC}$: recycled concrete property

$Pro_{c,CC}$: conventional concrete property

X: adjusted coefficient

2.2.3 Correction of code expressions

This analysis tries to correct the code expressions (Eurocode) [EURO04] to predict the recycled concrete properties with the same approximation degree as in conventional and recycled concretes. For said purpose, the theoretical value of any property is calculated taking into account the experimental value of the compressive strength. Using these results, the *"experimental property/calculated property"* ratios are obtained. If the ratios of recycled concretes are similar to those obtained with the conventional kind, it can be considered that the code expressions provide the same approximation degree both in recycled and conventional concretes when calculating the analysed property and, therefore, it is not necessary to modify these expressions. However, if these ratios decrease with the increase in the content of recycled coarse aggregate, the code expressions should be corrected using a coefficient which, in this case, will be adjusted by multivariable regression.

As already mentioned, the variables considered have been the replacement ratio and the recycled concrete coarse aggregate quality (considering it based on its water absorption) (Eq. 2-3). A different coefficient has been adjusted for each of the different mixing procedures considered.

$$\frac{Pro_{c,CC,exp}}{Pro_{c,CC,cal}} \neq \frac{Pro_{c,RC,exp}}{Pro_{c,RC,cal}} \Longrightarrow \frac{Pro_{c,CC,exp}}{Pro_{c,CC,cal}} = \frac{Pro_{c,RC,exp}}{Pro_{c,RC,cal} \cdot coefficient\ (f_{c,RC}, \%RCA, WA)} \quad (2)$$

$$Ratio = \frac{Pro_{c,exp}}{Pro_{c,cal}} \rightarrow Coefficient = \frac{Ratio\ recycled\ concrete}{Ratio\ conventional\ concrete} = \frac{Ratio\ RC}{Ratio\ CC} \quad (3)$$

Being:

$Pro_{c,CC,cal}$: calculated property of conventional concrete using code expressions

$Pro_{c,CC,exp}$: experimental property of conventional concrete

$Pro_{c,RC,cal}$: calculated property of recycled concrete using code expressions

$Pro_{c,RC,exp}$: experimental property of recycled concrete

Using this method, the proposed prediction expressions will be as follows (Eq. 4):

$$Pro_{c,RC} = CF\left(f_{c,RC}, \%RCA, WA\right) \cdot EUROCODE_{expresssion} \quad (4)$$

Being:

$Pro_{c,RC}$ = property of recycled concrete

CF = correction coefficient for the Eurocode expression

$f_{c,RC}$ = recycled concrete compressive strength

%RCA = replacement ratio (recycled concrete coarse aggregate percentage)

WA = recycled coarse aggregate water absorption

2.2.4 Adjustment of specific expressions

Lastly, in this work, as already mentioned, specific expressions to predict the studied properties have been adjusted. In this case, conventional concrete properties are not necessary because the expressions are adjusted using those which best fit the experimental results for recycled concrete. For said purpose, the Eurocode expressions have been used as a basis and modified to introduce the replacement ratio and the recycled concrete coarse aggregate quality (considering it, again, based on its water absorption). Also in this case, a different expression (Eq. 5) has been adjusted for each of the different mixing procedures considered, and the techniques used have been **multivariable regression and genetic programming**. With both techniques, part of the data (80%) has been kept for the training process while the remaining cases (20%) were left for the test process.

$$Pro_{c,RC} = \left(f_{c,RC}, \%RCA, WA\right)_{Expression} \quad (5)$$

Regarding genetic programming, Table IV-1 shows the default settings used in this work when running the algorithm. These parameters were chosen because they gave the best results in the initial tests. The input data to the algorithm was not standardized in the aim of achieving directly applicable formulas.

Table IV-1. Parameters used

Configuration parameters	Values
Population size	1000
Stopping criteria (maximum generation, epoch without improvement)	40000, 2000
Crossing rate	90%
Non-terminal selection rate	90%
Mutation probability	10%
Algorithms	Selection: Tournament Creation: Intermediate Mutation: Subtree
Elitist strategy	Yes
Parsimony	0 / 100
Initial tree height	3 / 6
Maximum tree height	6 / 9
Maximum mutation tree height	3 / 6
Terminal nodes	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, random real numbers [-1, 1]
Non-terminal nodes	+, - , *, /

Eq. 6 shows the fitness function used, where *n* is the number of datasets used, x_p is the predicted value by the individual and d_i is the desired value obtained from the experimental data, α is the level of parsimony and s_i is the size (number of nodes) of the individual. In essence, this fitness function uses the mean square error (MSE) penalized by the size of the individual. Thus, if two individuals have the same MSE value, the simple individual (less nodes) gets a better fit.

$$Fitness(i) = \frac{1}{n}\sum_{p=1}^{n}\left(x_p - y_p\right)^2 + \alpha \cdot S_i \tag{6}$$

In short, Figure IV-4 synthesises the methodology of this study.

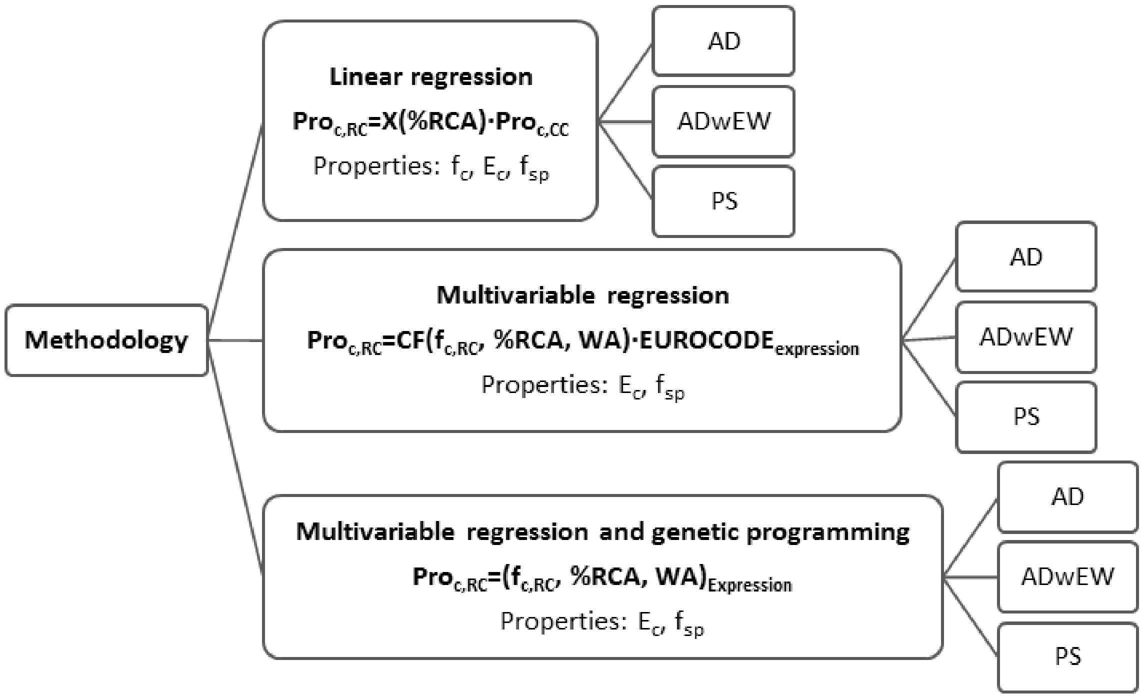


Figure IV-4. Methodology of the study

2.2.5 Adjustment goodness

Some statistical indexes have been used to evaluate the performance of the different adjustments. In this regard, when linear regression is used, the square of the Pearson product-moment correlation coefficient (coefficient of determination, R^2) can be considered a good index of the adjustment goodness.

When multivariable regression or genetic programming is used, the performance of the obtained expressions has been evaluated using four statistical indexes: the Pearson correlation coefficient (*r*), the mean squared error (MSE), the coefficient of variation (COV) and the mean average error (MAE) (Eq. 7-10). These indexes allow the author to determine which of the equations (proposed in this work or obtained from the literature) are the best for predicting the behaviour of recycled concrete.

$$r = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2(y_i-\bar{y})^2}} \tag{7}$$

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2 \tag{8}$$

$$COV = \frac{\sqrt{\frac{\sum_{i=1}^{n}(x_i-\bar{x})^2}{n}}}{\frac{\sum_{i=1}^{n}(x_i)}{n}} \cdot 100, \quad x = \frac{Actual\ value}{Predicted\ value} \tag{9}$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n} abs\ (x_i - y_i) \tag{10}$$

2.3 Compressive strength (f_c)

In general, recycled concrete compressive strength is lower than that of conventional concrete, and it decreases as the coarse aggregate substitution percentage increases. There are several interesting works [BRIT10, SILV15a, DUAN13a, TROC13] which have proposed different methods for predicting the compressive strength of recycled concretes. De Brito and Robles [BRIT10] using the data of four authors [GOME02, CARR05, LEIT01, KOU04] have studied the variation of the ratio between the 28 and 90-day compressive strengths of recycled and conventional concretes (fc_{RAC}/fc_{RC}), and the ratio between the densities (*D*), the water absorptions (*Wa*) of the mixture of aggregates and the 7-day compressive strengths of concretes (Eq. 11-13).

$$\frac{fc_{RAC}}{fc_{RC}} = a \cdot \left(\frac{Wa_{RAC}}{Wa_{RC}} - 1\right) + 1 \tag{11}$$

$$\frac{fc_{RAC}}{fc_{RC}} = b \cdot \left(1 - \frac{D_{RAC}}{D_{RC}}\right) + 1 \tag{12}$$

$$\frac{fc_{RAC}}{fc_{RC}} = c \cdot \left(1 - \frac{fc_{7RAC}}{fc_{7RC}}\right) + 1 \tag{13}$$

Recently, Silva et al. [SILV15a] suggested a model to predict strength loss based on the recycled aggregate content and quality. These authors show several relationships as follows (Eq. 14):

$$\frac{f_{cm-RAC}}{f_{cm-Control}} = a \cdot Replacement\ level\ (\%) + 1 \tag{14}$$

Other methods are based on Artificial Neural Networks (ANN) [DUAN13a, TROC13]. These investigators concluded that the ANN models could accurately predict compressive strength values.

As already mentioned, this study focuses on comparing conventional concrete compressive strength with that of recycled concrete. The objective was to discover how much this property can decrease when recycled concrete coarse aggregates are used, by analysing different incorporation ratios and mixing procedures, which have not been considered by other authors when developing their expressions but have a well-known influence on the properties of recycled concrete. The database analysis confirms that the reduction in compressive strength depends on the percentage of recycled aggregate and the concrete production method. Using linear regression, the correction coefficients (*X*) which allow engineers to estimate the decrease in compressive strength according to the expression (Eq. 15) are shown in Table IV-2. These allow engineers to estimate the expected compressive strength decrease for structural recycled concrete as a function of the recycled coarse aggregate content (*RCA*) and the production method.

$$f_{c,RC} = X \cdot f_{c,CC} \tag{15}$$

The square of the Pearson product-moment correlation coefficient (coefficient of determination, R^2) was calculated. In all cases, the value of R^2 is between 0.9 and 1, which indicates a very strong correlation (Table IV-2).

Table IV-2. Correction coefficients (*X*) to estimate $f_{c,RC}$

%RCA		AD	ADwEW	PS
	Data	147	140	89
100	X	0.897	0.888	0.828
	R^2	0.940	0.960	0.908
	Data	91	49	31
50	X	0.909	0.937	0.861
	R^2	0.975	0.911	0.874
	Data	83	38	37
20	X	0.964	0.969	0.936
	R^2	0.991	0.954	0.958

In Figure IV-5, Figure IV-6 and Figure IV-7, it can be seen that the lower the recycled aggregate percentage the lower the strength loss. Figure IV-5 to Figure IV-7 show the "r*ecycled concrete compressive strength vs conventional concrete compressive strength*" relationship for the different recycled percentages obtained using each of the production methods.

The PS method presents the highest reduction in compressive strength, due to the bleeding effect. In this method, as previously mentioned, the aggregates are pre-soaked for a fixed time before use. The pre-soaking time is usually adjusted taking into account the duration of time required for the water absorption of the recycled coarse aggregates.

The ADwEW method, however, employs an extra quantity of water which is added during the mixing process. This quantity of extra water is adjusted to a fixed percentage of water absorption at 24 h. With this method the reduction in compressive strength is lower and there is no need for the dosage of superplasticiser to be increased.

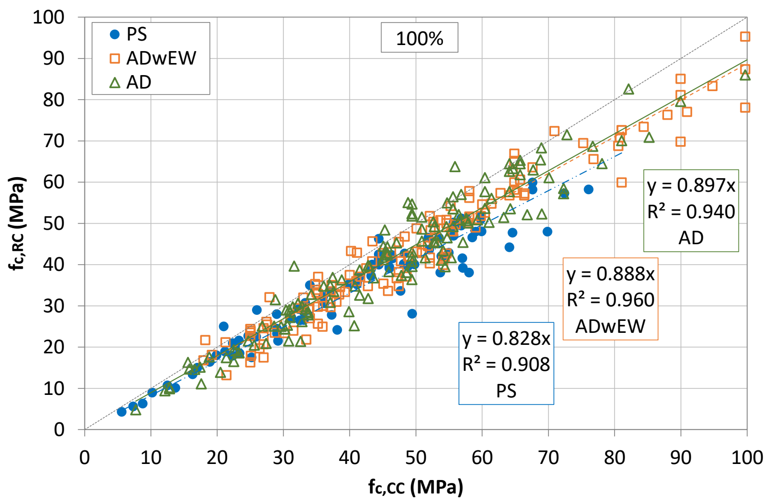


Figure IV-5. $f_{c,RC}$ vs $f_{c,CC}$ (100%)

Lastly, the AD method presents a compressive strength decrease lower than that obtained with the PS method and, in general, similar to the one obtained with ADwEW. However, with this method the high water absorption of the recycled aggregates reduces the free water in the mixes. This also leads to a loss in the workability of the fresh concrete which has to be compensated with a high dosage of superplasticiser.

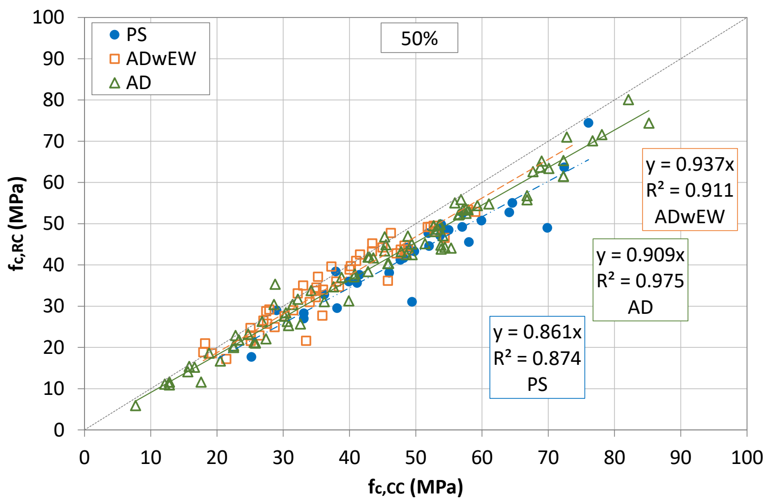


Figure IV-6. $f_{c,RC}$ vs $f_{c,CC}$ (50%)

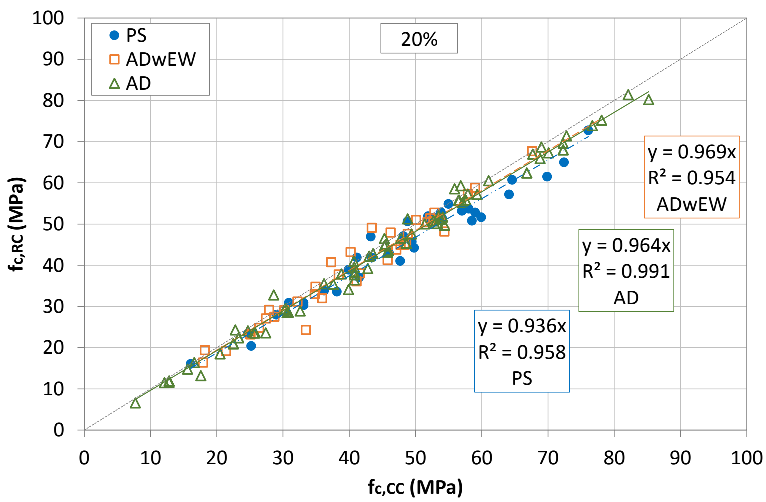


Figure IV-7. $f_{c,RC}$ vs $f_{c,CC}$ (20%)

2.4 Modulus of elasticity (E_c)

It is well know that the concrete elasticity modulus is related to the aggregates and the rigidity of the cement paste. The cement paste modulus is lower than that of the aggregate and the concrete [LOPE08]. Furthermore, recycled aggregates (with adhered mortar) present a modulus of elasticity lower than that of natural aggregates and, therefore, the recycled concrete modulus will be lower than that of conventional concrete. This is also due to the weakness of the new interfaces (new cement mortar – aggregate, old cement mortar – aggregate and old cement mortar - new cement mortar) which can lead to the progressive development of cracks, affecting the concrete deformability [BAIR93].

Most of the codes and standards suggest equations to predict the modulus of elasticity as a function of compressive strength. It is well known that these expressions are not suitable when recycled concrete is used. Therefore, many authors have proposed different expressions for its prediction (Table IV-3). However, these expressions have been adjusted with the authors' particular results and, so, it has been revealed that they present some scatterings when other researchers' results are analysed.

Table IV-3. Authors' equations - $E_{c,RC}$

Reference	Equation
Ravi(1985)a [RAVI85]	$E_c = 7770 \cdot f_c^{0.33}$
Ravi(1985)b [RAVI85]	$E_c = 4630 \cdot f_c^{0.5}$
Ravi(1987) [RAVI87]	$E_c = 3480 \cdot f_c^{0.5} + 13050$
Tang(2010) [TANG10]	$E_c = 4450 \cdot f_c^{0.5}$
Bair(1993) [BAIR93]	$E_c = \alpha \cdot f_c^{0.5}$; $\alpha = \alpha(r) = 5780 - 1340 \cdot r \ (0 \leq r \leq 1)$
Dhir(1999) [DHIR99]	$E_c = 370 \cdot f_c + 13100$
Dill(1998) [DILL98]	$E_c = 634.43 \cdot f_c + 3057.6$
Mell(1999) [MELL99]	$E_c = 378 \cdot f_c + 8242$
Xiao(2006) [XIAO06]	$E_c = \dfrac{10^5}{2.8 + \dfrac{40.1}{f_c}}$
Katz(2003) [KATZ03]	$E_c = 0.043 \cdot \rho^{1.5} \cdot f_c^{0.5}$
Kaki(1988) [KAKI88]	$E_c = 1.9 \cdot 10^5 \cdot \left(\dfrac{\rho}{2300}\right)^{1.5} \cdot \left(\dfrac{f_c}{2000}\right)^{0.5}$
Li(2008) [LI08]	$E_c = 5.5 \cdot 10^3 \cdot f_c^{0.5} \cdot \left(\dfrac{\rho}{2400}\right) \cdot \left(1 - \dfrac{r}{\alpha}\right)$; $\alpha = 2.2876 \cdot r + 0.1288 \ (0 \leq r \leq 1)$
Cori(2010)a [CORI10a]	$E_c = 18800 \cdot \sqrt[3]{\dfrac{0.83 \cdot f_{cu}}{10}}$
Cori(2010)b [CORI10a]	$E_c = 909 \cdot f_{cu} + 8738$
Zilc(2001) [ZILC01]	$E_c = 9100 \cdot (f_c + 8)^{1/3} \cdot \left(\dfrac{\rho}{2400}\right)^2$

Where:

$E_c = Modulus\ of\ elasticity\ (MPa)$

$f_c\ or\ f_{cu}\ = Compressive\ strength\ (MPa)$

$\rho = Density\ (kg/m^3)$

$r = Replacement\ percentage$

Furthermore, in recent years, as with compressive strength, methods have been developed by different authors [BRIT10, DUAN13b, BEHN15] to predict the recycled concrete modulus. De Brito and Robles [BRIT10] using the data of four authors [GOME02, CARR05, LEIT01, KOU04] have studied the variation of the ratio between the 28 and 90-day modulus of elasticity of recycled and conventional concretes (Ec_{RAC}/Ec_{RC}), and the ratio between the densities (*D*), the water absorptions (*Wa*) of the mixture of aggregates and the 7-day compressive strengths of concretes (Eq. 16-18).

$$\frac{Ec_{RAC}}{Ec_{RC}} = a \cdot \left(\frac{Wa_{RAC}}{Wa_{RC}} - 1\right) + 1 \tag{16}$$

$$\frac{Ec_{RAC}}{Ec_{RC}} = b \cdot \left(1 - \frac{D_{RAC}}{D_{RC}}\right) + 1 \tag{17}$$

$$\frac{Ec_{RAC}}{Ec_{RC}} = c \cdot \left(1 - \frac{fc_{7RAC}}{fc_{7RC}}\right) + 1 \tag{18}$$

On the other hand, Behnood et al. [BEHN15] developed the M5 tree algorithm to model the recycled concrete modulus. They assume the general expression (Eq. 19) or (Eq. 20) and develop the model in the form of logarithms, as the method is only able to produce linear relationships. The results show that the model can be an accurate tool for predicting the modulus of elasticity of recycled aggregate concrete.

$$E_{RAC} = a(f_{cu})^{b} \left(\frac{w}{c}\right)^{c} \left(\frac{CA}{C}\right)^{d} (r)^{e} \left(\frac{FA}{TA}\right)^{f} (SG_{SSD})^{g} (W_a)^{h} \tag{19}$$

$$E_{RAC} = a'(f_{cu})^{b'} \left(\frac{w}{c}\right)^{c'} \left(\frac{CA}{C}\right)^{d'} (r)^{e'} \left(\frac{FA}{TA}\right)^{f'} \tag{20}$$

Duan et al. [DUAN13b] explored the applicability of artificial neural networks (ANN) in modelling the recycled aggregate concrete modulus. Their results show that the constructed ANN models can accurately predict the elastic modulus of concrete made with recycled aggregates derived from different sources. However, these techniques [DUAN13b, BEHN15] do not provide structural designers with a clear mathematical expression.

As shown, the prediction of the recycled concrete modulus is a question that remains unsolved. In this work, using a database with over 300 datasets, a study of the relationship between recycled and conventional concrete modulus has been carried out. After which, with over 400 datasets and using multivariable regression and genetic programming, expressions to predict the structural recycled concrete modulus have been developed.

2.4.1 Conventional concrete property vs recycled concrete property

In this first step, and using linear regression (Figure IV-8 and Figure IV-9), a coefficient to estimate the recycled concrete modulus as a function of that of conventional concrete has been adjusted (Eq. 21). This coefficient takes into account the recycled content and the mixing procedure used. The adjustment goodness has been evaluated with the coefficient of determination, R^2 (Table IV-4).

$$E_{c,RC} = X \cdot E_{c,CC} \tag{21}$$

As in the compressive strength analysis, the PS method presents the highest reduction in the elasticity modulus, which is, once again, due to the bleeding effect. The AD method shows the lowest reductions and, lastly, the ADwEW method presents an elasticity modulus decrease lower than that obtained with the PS method and higher than that with the AD method (Figure IV-8, Figure IV-9).

Table IV-4. Correction coefficients (*X*) to estimate $E_{c,RC}$

Production method		<50%	50-100%
AD	Data	36	78
	X	0.948	0.856
	R^2	0.830	0.510
ADwEW	Data	19	73
	X	0.882	0.856
	R^2	0.931	0.763
PS	Data	39	68
	X	0.886	0.792
	R^2	0.437	0.579

Figure IV-8 and Figure IV-9 show the "*recycled concrete elasticity modulus vs conventional concrete elasticity modulus*" relationship for the different replacement percentages and different mixing procedures.

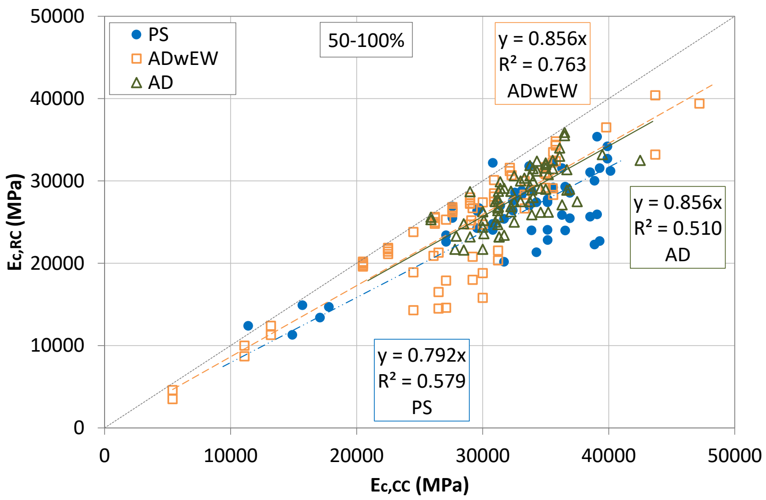


Figure IV-8. $E_{c,RC}$ vs $E_{c,CC}$ (50-100%)

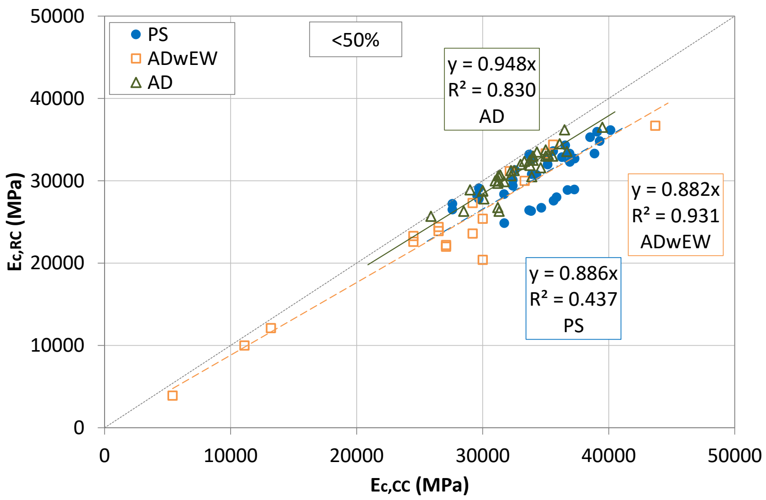


Figure IV-9. $E_{c,RC}$ vs $E_{c,CC}$ (<50%)

The only goal of this method (*conventional concrete modulus vs recycled concrete modulus*) is to obtain information as the recycled concrete modulus cannot be predicted with this analysis technique as a conventional concrete reference is needed.

2.4.2 Correction of code expressions

The second step is to analyse whether or not it is necessary to adapt the proposed code expression (Eurocode) [EURO04] to predict the elasticity modulus of recycled concrete with the same approximation degree as that of conventional concrete. In Figure IV-10, Figure IV-11 and Figure IV-12 the "*experimental modulus/calculated modulus*" ratio of recycled vs conventional concretes is shown for each mixing procedure (AD, ADwEW and PS).

As observed, the ratios of conventional concretes are higher than those obtained with recycled concretes. This means that the code expression will not provide the same approximation degree in recycled concretes as in conventional ones when calculating the modulus. Therefore, it is necessary to modify it by introducing a correction coefficient.

Hence, in order to get the same approximation degree as with the Eurocode expression, i.e. to obtain the same "*experimental modulus/calculated modulus*" ratio in conventional and recycled concretes using said expression, a correction coefficient (*CF*) has been adjusted by multivariable regression. The variables considered have been the replacement ratio and the recycled concrete coarse aggregate quality (considering it based on its water absorption). A different coefficient has been adjusted for each of the different mixing procedures considered. More variables affecting the results may be considered to improve the proposed models. However, as this occurs with the same relationship for conventional concrete, the cost (complexity of the model) / benefit (reliability of the prediction) was taken into account and it was decided not to increase the number of variables.

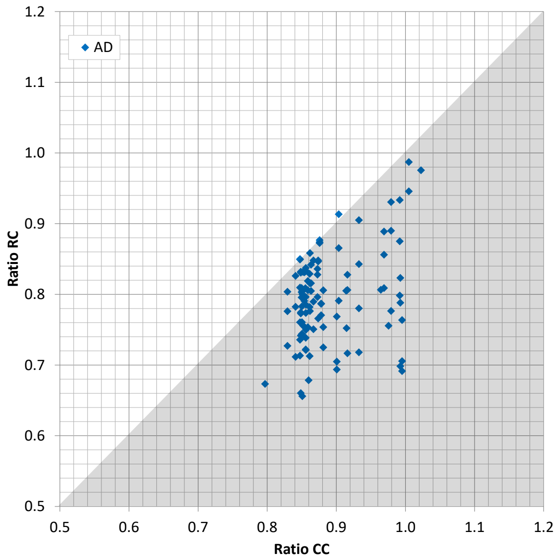


Figure IV-10. Ratio RC vs Ratio CC (AD method)

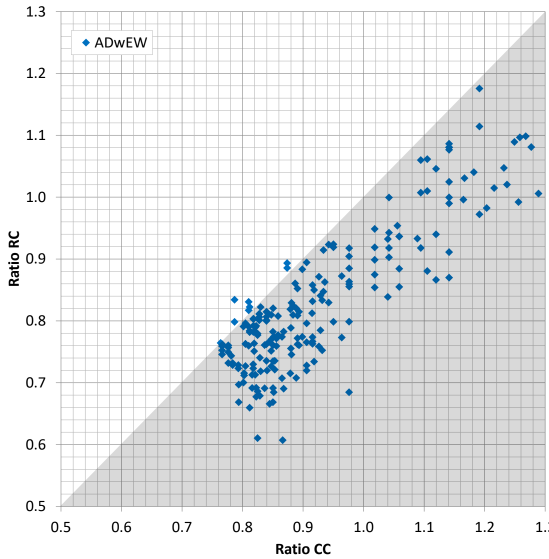


Figure IV-11. Ratio RC vs Ratio CC (ADwEW method)

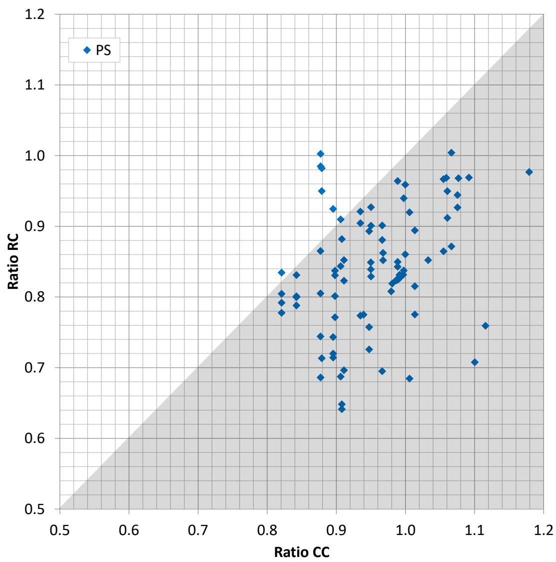


Figure IV-12. Ratio RC vs Ratio CC (PS method)

Then, according to sub-section “Methodology – Correction of code expressions”, the expression is as follows (Eq. 22):

$$E_{c,RC} = CF\left(f_{c,RC}, \%RCA, WA\right) \cdot EUROCODE_{expresssion} \tag{22}$$

Where:

$$EUROCODE_{expresssion} = Ec_{cal} = 22000 \cdot \left(\frac{fc}{10}\right)^{0.3} \tag{23}$$

$$CF(f_{c,RC},\%RCA,WA)=\frac{Ratio\ recycled\ concrete}{Ratio\ conventional\ concrete}=\frac{Ec_{exp,RC}/Ec_{cal,RC}}{Ec_{exp,CC}/Ec_{cal,CC}} \quad (24)$$

In this work, the following general expression has been selected to adjust the coefficient *CF* (Eq. 25):

$$CF=\frac{\left(1-b\cdot\frac{\%RCA}{100}\cdot\frac{WA}{5}\right)}{\left(\frac{f_{c,RC}}{10}\right)^{\left(0.3\cdot a\cdot\frac{\%RCA}{100}\right)}\cdot\left(1-d\cdot\frac{\%RCA}{100}\right)} \quad (25)$$

Through multivariable regression, the parameters *a*, *b* and *d* have been adjusted (Table IV-5). The adjustment performance has been analysed using the Pearson correlation coefficient (*r*) and the mean squared error (MSE).

Table IV-5. Adjustment of the correction coefficient (*CF*) to calculate the RC modulus

Production	Data		Adjustment			*r*		MSE	
method	Training	Testing	*a*	*b*	*d*	Training	Testing	Training	Testing
AD	90	22	-0.1268	-0.0037	-0.2649	0.5332	0.4146	0.004051	0.003528
ADwEW	164	42	-0.0697	0.0677	-0.1044	0.4019	0.4936	0.003843	0.003038
PS	73	17	-0.3433	0.1842	-0.1120	0.5106	0.7252	0.007868	0.004857

Figure IV-13, Figure IV-14 and Figure IV-15 show the *predicted value vs actual value*" relationship for the *CF* coefficient.

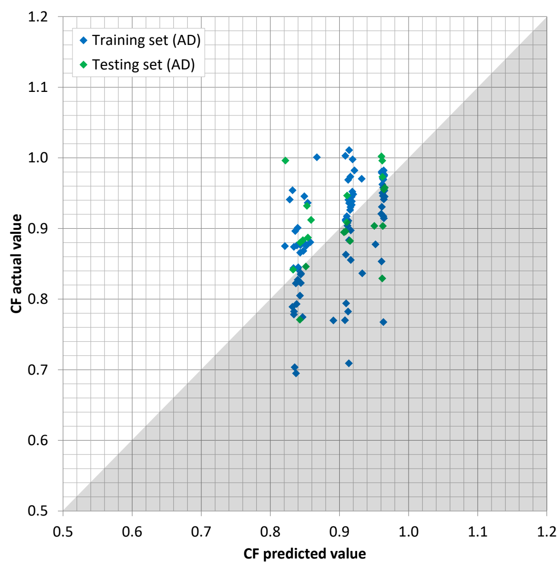


Figure IV-13. CF predicted value vs CF actual value. Training and testing performance (AD method)

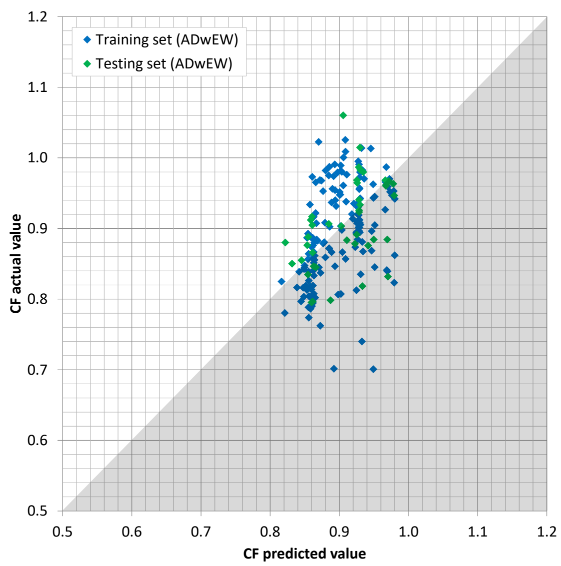


Figure IV-14. CF predicted value vs CF actual value. Training and testing performance (ADwEW method)

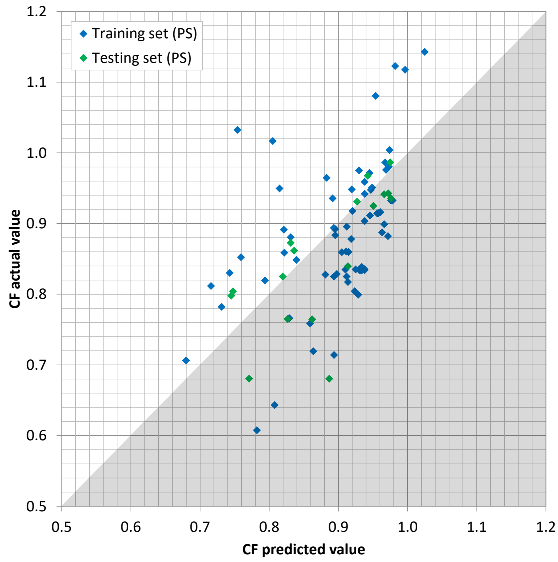


Figure IV-15. CF predicted value vs CF actual value. Training and testing performance (PS method)

Figure IV-16, Figure IV-17 and Figure IV-18 show the new "*experimental modulus/calculated modulus*" ratios of recycled vs conventional concretes for each mixing procedure. In this case the recycled concrete modulus was predicted using the Eurocode expression corrected with the adjusted coefficient. As observed, at this stage the ratios of recycled concretes are similar to those obtained with conventional kinds.

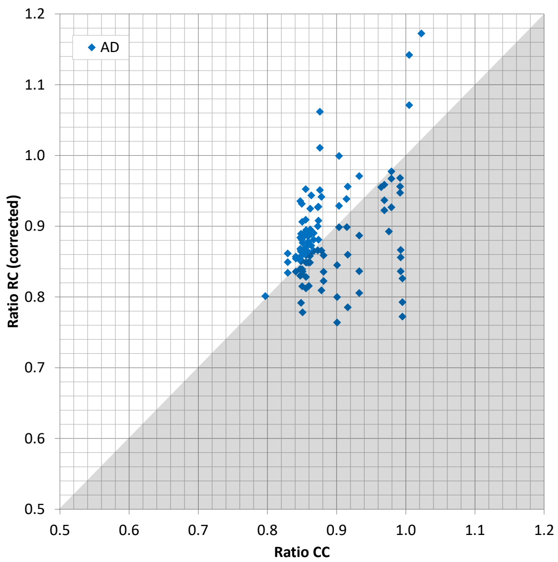


Figure IV-16. Ratio RC corrected with CF vs Ratio CC (AD method)

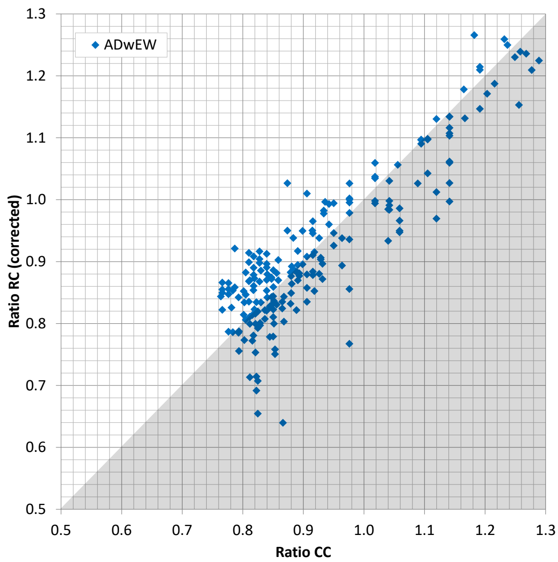


Figure IV-17. Ratio RC corrected with CF vs Ratio CC (ADwEW method)

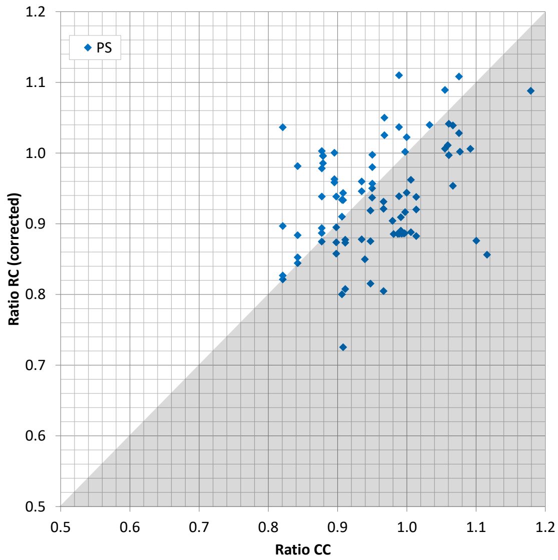


Figure IV-18. Ratio RC corrected with CF vs Ratio CC (PS method)

2.4.3 Adjustment of specific expressions

Lastly, in this work, specific expressions to predict the modulus of elasticity have been adjusted. For said purpose, the Eurocode expression has been taken as a basis, but it has been modified to introduce the replacement ratio and the recycled concrete coarse aggregate quality (considering it, again, based on its water absorption). Also in this case, a different expression has been adjusted for each of the different mixing procedures considered, and the techniques used have been multivariable regression and genetic programming.

The following general expression has been selected as a basis for the prediction of the recycled modulus of elasticity using multivariable regression (Eq. 26).

$$E_{c,RC} = 22000 \cdot \left(\frac{f_{c,RC}}{10}\right)^{\left[0.3\cdot\left(1-a\cdot\frac{\%RCA}{100}\right)\right]} \cdot \frac{\left(1-b\cdot\frac{\%RCA}{100}\cdot\frac{WA}{5}\right)}{\left(1-d\cdot\frac{\%RCA}{100}\right)} \tag{26}$$

Table IV-6 shows the parameters *a*, *b* and *d* adjusted using multivariable regression.

Table IV-6. Parameters *a, b* and *d* adjusted using multivariable regression - $E_{c,RC}$ expression

Production method	*a*	*b*	*d*
AD	-0.6378	-0.4449	-1.4893
ADwEW	-0.7539	-0.1403	-1.0534
PS	-0.4143	0.1636	-0.2700

When genetic programming is used, the first step is the selection of the type of equation to be optimized. In this case, after different tests it was decided to work with an equation that guides the search process (Eq. 27). Therefore, Eq. 27 has been established to be optimized using genetic programming.

$$E_{c,RC} = 22000 \cdot \left(\frac{f_{c,RC}}{10}\right)^{\left[\frac{1}{3}\cdot\left(1-\frac{\%RCA}{100}\cdot Branch_1\right)\right]} \cdot \left(1 - \frac{\%RCA}{100} \cdot Branch_2\right) \tag{27}$$

Where:

$Branch_1 = f\left(\frac{\%RCA}{100}, \frac{WA}{5}\right)$ and $Branch_2 = f\left(\frac{\%RCA}{100}, \frac{WA}{5}\right)$

The rules for generating the branches have been as follows: both include two variables, *%RCA* and *water absorption (WA)*, and the maximum number of occurrences of these variables, equal in both branches, has been restricted to 2.

Apart from these limitations, the equation has been generated by the terminal and non-terminal nodes shown in table 1. At the end of the genetic programming, one final expression was obtained for each mixing procedure. The "shape" of each branch of the equation has been determined and the final results are as follows.

For the AD method (Eq. 28-29):

$$Branch_1 = -\frac{\frac{WA}{5}}{19\cdot\left(5.09\cdot\frac{\%RCA}{100} - \frac{5\cdot\frac{\%RCA}{100}}{\frac{WA}{5}}\right)} \tag{28}$$

$$Branch_2 = \frac{1}{\frac{\%RCA}{100}+10} + \frac{1}{5\cdot\frac{\%RCA}{100}} \tag{29}$$

For the ADwEW method (Eq. 30-31):

$$Branch_1 = \frac{0.0207\cdot\left(\frac{0.0443}{\frac{\%RCA}{100}}+0.2003\right)}{2\cdot\frac{WA}{5}-0.8552} \tag{30}$$

$$Branch_2 = \frac{0.2211}{\frac{\%RCA}{100}+0.2078} + \frac{0.003067}{\frac{WA}{5}\cdot\left(\frac{\%RCA}{100}+0.2003\right)\cdot\left(\frac{WA}{5}-0.8518\right)} + 0.0442 \tag{31}$$

And for the PS method (Eq. 32-33):

$$Branch_1 = \left(0.0521 \cdot \frac{WA}{5} - 0.0521\right) \cdot \left(\frac{0.2027}{\frac{WA}{5}\cdot\left(\frac{\%RCA}{100}-0.2027\right)} + \frac{0.52}{\frac{\%RCA}{100}}\right) \tag{32}$$

$$Branch_2 = 0.1202 \cdot \frac{WA}{5} + \frac{0.004188}{\frac{WA}{5}-0.9616} + \frac{0.13}{\frac{\%RCA}{100}} - 0.03346 \tag{33}$$

The obtained equations have been analysed comparing their behaviour with those obtained in the literature. In all cases, the equations obtained with multivariable regression show *r*, MSE and MAE values better than the best ones in the literature. The COV value is the only index that does not improve the accuracy of the other authors' expressions. With the genetic programming technique, the equations obtained always show the best statistical indexes (Table IV-7, Table IV-8 and Table IV-9).

Table IV-7. Statistical indexes for AD method – E_c expressions

AD method	Training set				Testing set			
	r	MSE	COV	MAE	*r*	MSE	COV	MAE
Multivariable	0.8080	5.6644	8.9822	1.8012	0.8483	4.4249	8.2336	1.7535
Genetic Prog.	0.8971	2.0882	5.2293	1.0869	0.9048	1.9495	4.7249	1.0407
Ravi(1985)a	0.7388	4.8439	8.2254	1.6443	0.7318	4.3589	7.4571	1.7028
Ravi(1985)b	0.7435	29.6662	9.7691	5.0735	0.7332	31.3949	9.8803	4.8797
Ravi(1987)	0.7435	95.0422	8.1404	9.4776	0.7332	92.6756	7.3940	9.3359
Tang(2010)	0.7435	18.6806	9.7691	3.9542	0.7332	20.0183	9.8803	3.7258
Bair(1993)	0.7970	71.7218	12.1098	7.6389	0.8369	65.8072	11.3012	7.5032
Dhir(1999)	0.7528	25.0932	10.6841	4.4864	0.7325	29.8629	11.3283	4.4123
Dill(1998)	0.7528	96.2984	18.6008	8.5445	0.7325	120.3503	20.4147	8.9567
Mell(1999)	0.7528	10.4539	12.9597	2.4701	0.7325	14.2170	14.0001	3.3344
Xiao(2006)	0.7043	6.5197	8.6883	2.0432	0.7111	6.0185	7.5163	2.1443
Cori(2010)a	0.7389	8.4788	8.2333	2.5301	0.7319	7.2522	7.4800	2.0670
Cori(2010)b	0.7528	862.1747	16.5144	27.8252	0.7325	957.4963	18.0433	28.9787

Table IV-8. Statistical indexes for ADwEW method – E_c expressions

ADwEW method	Training set				Testing set			
	r	MSE	COV	MAE	*r*	MSE	COV	MAE
Multivariable	0.8078	14.4707	14.4482	2.9841	0.7597	17.6657	17.7650	3.2886
Genetic Prog	0.8671	10.6524	11.3337	2.5508	0.8460	11.8494	12.6730	2.7795
Ravi(1985)a	0.7980	18.9172	14.8641	3.0809	0.7350	23.4009	15.3022	3.6288
Ravi(1985)b	0.8055	27.0215	14.3744	4.4556	0.7504	24.4460	17.5507	4.1943
Ravi(1987)	0.8055	89.0661	14.8382	8.7137	0.7504	70.4493	14.9410	7.2888
Tang(2010)	0.8055	19.7364	14.3744	3.6821	0.7504	20.1191	17.5507	3.6363
Bair(1993)	0.7949	35.6756	15.4812	5.0392	0.7821	37.5993	19.7464	5.4085
Dhir(1999)	0.8155	23.8056	14.0323	4.0408	0.7823	24.0211	17.3830	4.0591
Dill(1998)	0.8155	84.6957	23.7461	7.1277	0.7823	94.7654	31.1998	7.7234
Mell(1999)	0.8155	19.0480	15.9246	3.2249	0.7823	31.4233	20.9082	4.2685
Xiao(2006)	0.7373	26.1691	16.8695	3.5221	0.6365	32.8391	17.0190	4.1565
Cori(2010)a	0.7982	18.7484	14.8227	3.4553	0.7354	18.7913	15.3071	3.4348
Cori(2010)b	0.8155	755.9524	20.4253	24.9357	0.7823	731.0634	27.1253	23.4059

Lastly, on Figure IV-19, Figure IV-20, Figure IV-21, Figure IV-22, Figure IV-23 and Figure IV-24 the "*predicted value vs experimental value*" relationship can be observed for the group of data used to adjust the equations (training set) and the group of data used to validate them (testing set). Both relationships are shown for the equation obtained using multivariable regression and the equation optimized using genetic programming.

Table IV-9. Statistical indexes for PS method – E_c expressions

PS method	Training set				Testing set			
	r	MSE	COV	MAE	*r*	MSE	COV	MAE
Multivariable	0.7979	7.0012	9.5912	2.2401	0.7440	10.7998	11.3794	2.5861
Genetic Prog	0.8616	4.1204	7.5443	1.5561	0.8208	6.3237	8.5317	1.8507
Ravi(1985)a	0.7173	11.7832	10.1134	2.8113	0.5120	12.5912	12.5436	2.8763
Ravi(1985)b	0.7155	10.3339	10.4826	2.6425	0.5066	25.0926	13.1288	3.8661
Ravi(1987)	0.7155	56.3982	10.2386	6.9763	0.5066	85.5450	12.5967	8.5287
Tang(2010)	0.7155	8.4362	10.4826	2.3580	0.5066	18.4200	13.1288	3.0277
Bair(1993)	0.7155	27.7789	13.0451	4.5863	0.7240	41.7745	13.5941	5.5709
Dhir(1999)	0.7049	9.1564	10.6955	2.4212	0.4884	20.5140	13.5128	3.1397
Dill(1998)	0.7049	24.0701	17.1268	3.6791	0.4884	50.7502	18.9928	5.1458
Mell(1999)	0.7049	28.3870	12.0010	4.6077	0.4884	22.0852	14.7788	3.8679
Xiao(2006)	0.7123	13.0556	10.3578	2.9247	0.5324	12.9807	12.6062	3.0439
Cori(2010)a	0.7172	7.8622	10.1009	2.2739	0.5119	13.8623	12.5414	2.6316
Cori(2010)b	0.7049	385.3592	14.9647	18.2214	0.4884	565.0563	17.2976	22.2844

Both techniques provide an expression that can be suggested to calculate the modulus of recycled aggregate concrete. The adjustment is quite similar in both cases. However, the equation optimized using genetic programming has shown better statistical indexes whereas the equation obtained using multivariable regression is simpler.

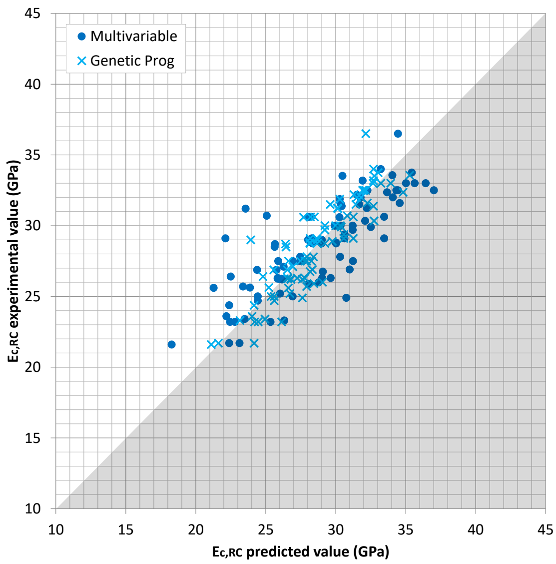


Figure IV-19. $E_{c,RC}$ predicted value vs $E_{c,RC}$ experimental value. Training performance (AD method)

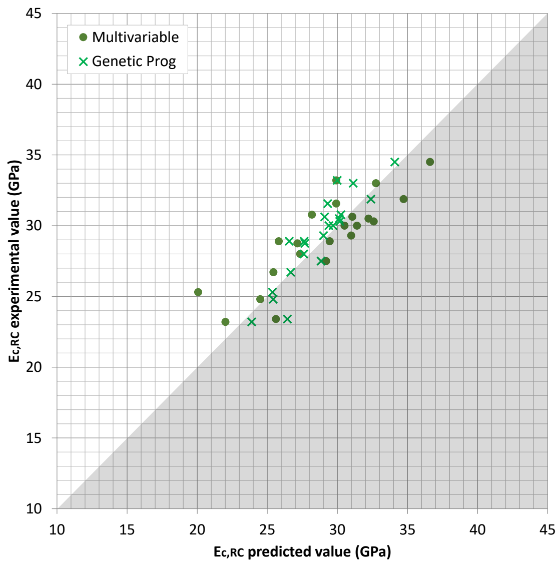


Figure IV-20. $E_{c,RC}$ predicted value vs $E_{c,RC}$ experimental value. Testing performance (AD method)

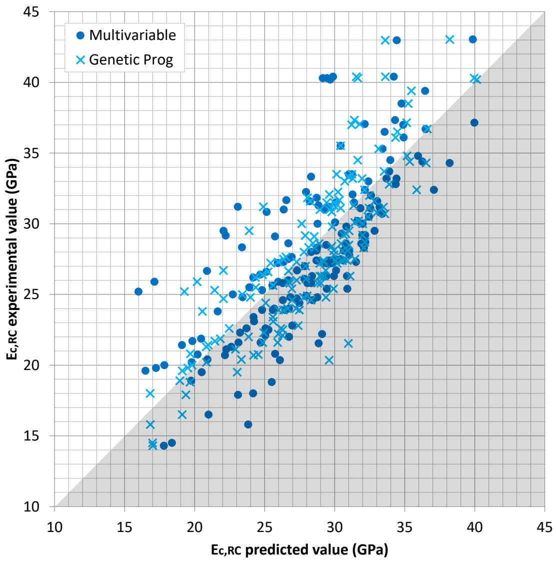


Figure IV-21. $E_{c,RC}$ predicted value vs $E_{c,RC}$ experimental value. Training performance (ADwEW method)

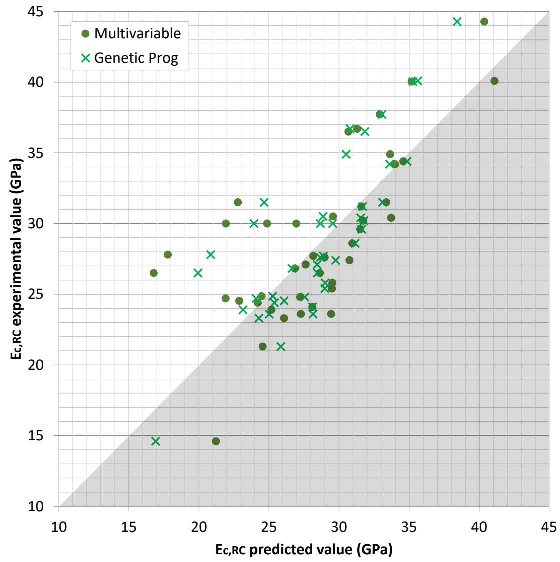


Figure IV-22. $E_{c,RC}$ predicted value vs $E_{c,RC}$ experimental value. Testing performance (ADwEW method)

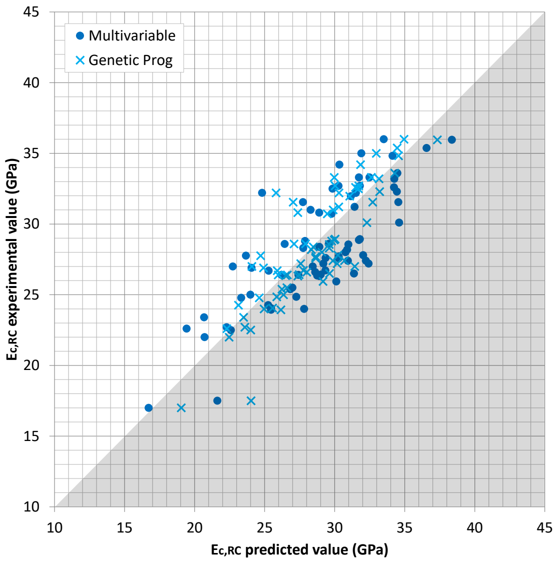


Figure IV-23. $E_{c,RC}$ predicted value vs $E_{c,RC}$ experimental value. Training performance (PS method)

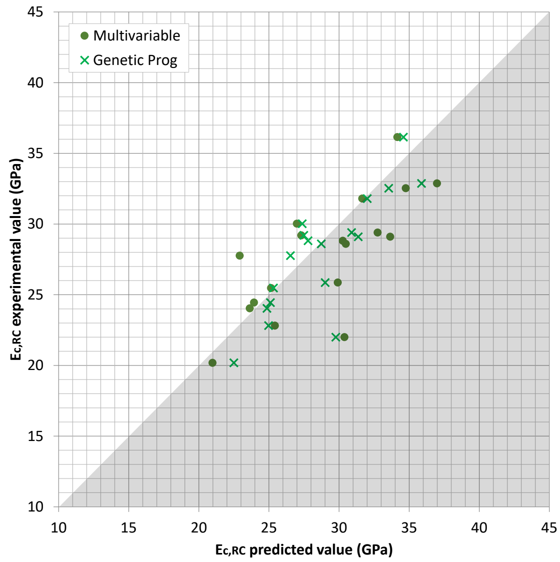


Figure IV-24. $E_{c,RC}$ predicted value vs $E_{c,RC}$ experimental value. Testing performance (PS method)

2.5 Splitting tensile strength (f_{sp})

The same analysis for the modulus of elasticity has been carried out for the splitting tensile strength, although the results obtained with this parameter show higher scatterings than those obtained for the modulus.

For both the compressive strength and the modulus E_c, there are several interesting works [BRIT10, SILV15b] which have tried to predict the splitting tensile strength of recycled aggregate concretes. Again, De Brito and Robles [BRIT10] using the data of two authors [GOME02, KOU04] studied the variation of the ratio between the 28 and 90-day splitting tensile strength of recycled concrete and that of conventional concrete (fsp_{RAC}/fsp_{RC}), and the ratio between the densities (*D*), the water absorptions (*Wa*) of the mixture of aggregates and the 7-day compressive strengths of concretes (Eq. 34-36).

$$\frac{fsp_{RAC}}{fsp_{RC}} = a \cdot \left(\frac{Wa_{RAC}}{Wa_{RC}} - 1\right) + 1 \tag{34}$$

$$\frac{fsp_{RAC}}{fsp_{RC}} = b \cdot \left(1 - \frac{D_{RAC}}{D_{RC}}\right) + 1 \tag{35}$$

$$\frac{fsp_{RAC}}{fsp_{RC}} = c \cdot \left(1 - \frac{fc_{7RAC}}{fc_{7RC}}\right) + 1 \tag{36}$$

These authors also stated that the results of the splitting tensile strength graphs obtained, confirm the scatter of the test results for this property in different campaigns.

Recently, Silva et al. [SILV15b] suggested that the tensile strength is also affected, like the compressive strength [SILV15a], by the recycled aggregate content, size, type and quality. They have found that the relationship between tensile and compressive strengths appears to have been unaffected by the use of recycled aggregate. They conclude that the inclusion of recycled aggregates causes a proportional decrease in both tensile and compressive strengths, at a rate that follows the same relationship as observed in conventional concrete.

However, other authors suggest that the equations proposed by codes and standards to predict the splitting tensile strength as a function of the compressive strength are not suitable when recycled concrete is used. In this regard, these authors [XIAO06, LI08, KATZ03], based on their experimental campaigns, have proposed specific expressions adjusted to predict the recycled concrete splitting tensile strength (Table IV-10).

Table IV-10. Authors' equations - $f_{sp,RC}$

Reference	Equation
Xiao(2006) [XIAO06]	$f_{sp} = 0.24 \cdot f_{cu}^{0.65}$
Katz(2003) [KATZ03]	$f_{sp} = 0.59 \cdot \sqrt{f_c}$
Li(2008) [LI08]	$f_t = (0.24 - 0.06 \cdot r) \cdot f_{cu}^{2/3}$

Again in this work, using a database with over 330 datasets, studies on the relationship between recycled and conventional concrete splitting tensile strength have been analysed. Then, with over 480 datasets, the "*experimental property/calculated property*" ratios have been obtained. If these are similar in conventional and recycled concretes, it can be considered that code expressions provide the same approximation degree in both recycled and conventional concretes and, therefore, it is not necessary to modify these expressions. Otherwise, a correction coefficient to predict structural recycled concrete splitting tensile strength should be proposed. Lastly, with multivariable regression and genetic programming, the relationship between splitting tensile and compressive strength in recycled concretes has been optimized, taking into account the replacement percentage, the quality of the recycled aggregate and the mixing procedure used.

2.5.1 Conventional concrete property vs recycled concrete property

In this first step, and using linear regression (Figure IV-25 and Figure IV-26), a coefficient to estimate recycled concrete splitting tensile strength as a function of that of conventional concrete has been adjusted (Eq. 37). This coefficient takes into account the recycled content and the mixing procedure used. The suitability of the adjustment has been evaluated by the coefficient of determination, R^2 (Table IV-11).

$$f_{sp,RC} = X \cdot f_{sp,CC} \tag{37}$$

Table IV-11. Correction coefficients (*X*) to estimate $f_{sp,RC}$

Production method		<50%	50-100%
AD	Data	47	135
	X	0.933	0.913
	R^2	0.962	0.924
ADwEW	Data	11	78
	X	0.946	0.902
	R^2	0.959	0.931
PS	Data	24	45
	X	0.919	0.888
	R^2	0.635	0.642

The water demand of recycled aggregates in air-dry condition without any adjustment dismisses the effective water to cement ratio, which leads to obtaining the lowest reductions in the mechanical properties of recycled concretes made using the AD method. This fact also explains that some recycled concretes made using this method present higher splitting tensile strength than those obtained with their control concretes (Figure IV-25). It can be observed that the ADwEW method presents recycled concretes with a very similar behaviour to those produced using the AD method.

As in the compressive strength analysis, the PS method presents the highest reduction in the splitting tensile strength, higher than that of the ADwEW method (Figure IV-25 and Figure IV-26). This can be explained, again, by the bleeding effect and, according to Silva et al. [SILV15b] and Ferreira et al. [FERR11], by the “nailing effect”, which is caused by the cement paste filling the surface pores of aggregate particles, achieving an improved bond strength.

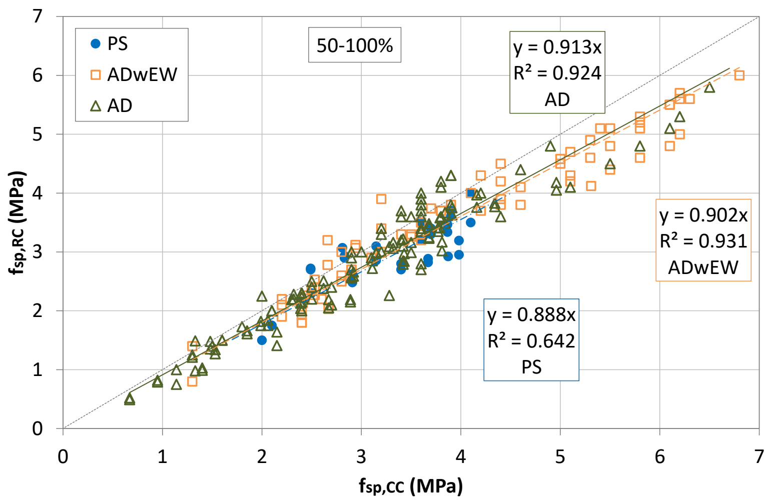


Figure IV-25. $f_{sp,RC}$ vs $f_{sp,CC}$ (50-100%)

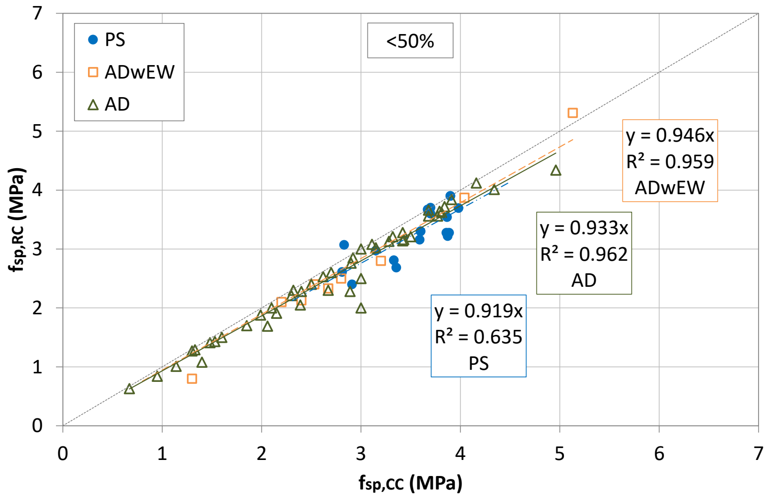


Figure IV-26. $f_{sp,RC}$ vs $f_{sp,CC}$ (<50%)

2.5.2 Correction of code expressions

As in the elasticity modulus section, the second step is to analyse whether or not it is necessary to adapt the proposed Eurocode expression [EURO04] for the splitting tensile strength when recycled concrete is used. In Figure IV-27, Figure IV-28 and Figure IV-29 the "*experimental splitting tensile strength/calculated splitting tensile strength*" ratio of recycled and conventional concretes is shown for each mixing procedure (AD, ADwEW and PS).

It can be observed (Figure IV-27 and Figure IV-28) that the points (ratio CC vs ratio RC) are noticeably closed and around (up and down) the midline in the cases of the AD and ADwEW methods. This means that the code expression provides the same approximation degree in recycled concretes as in conventional ones when calculating splitting tensile strength. Therefore, it is not necessary to modify the proposed Eurocode expression with any correction coefficient. In these cases, the use of the experimental compressive strength for the prediction of the splitting tensile strength is enough to get the same approximation degree in recycled concretes as in conventional ones.

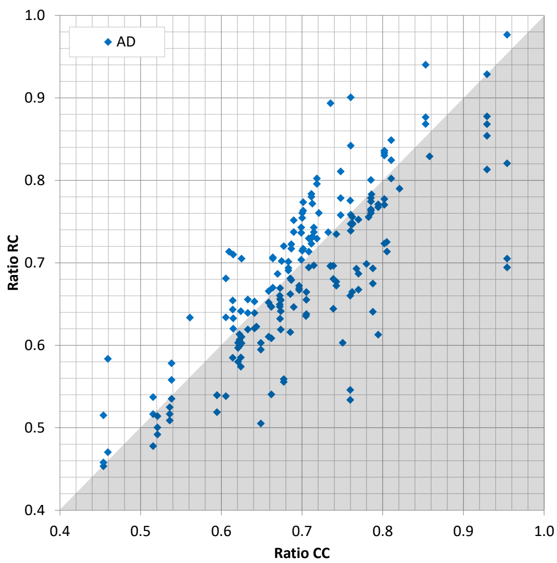


Figure IV-27. Ratio RC vs Ratio CC (AD method)

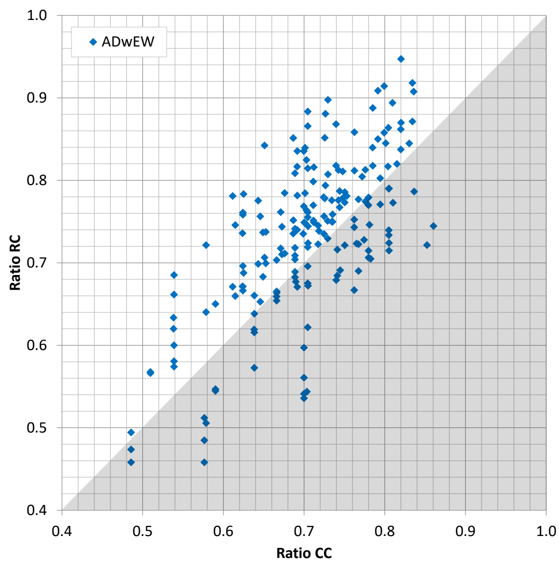


Figure IV-28. Ratio RC vs Ratio CC (ADwEW method)

In the case of the PS method (Figure IV-29), high scatterings can be observed (points are not as close as in the AD and ADwEW methods). However, they do not show a clear trend in their position, being around the midline. In this regard, it can be considered once again, that a correction coefficient is not necessary.

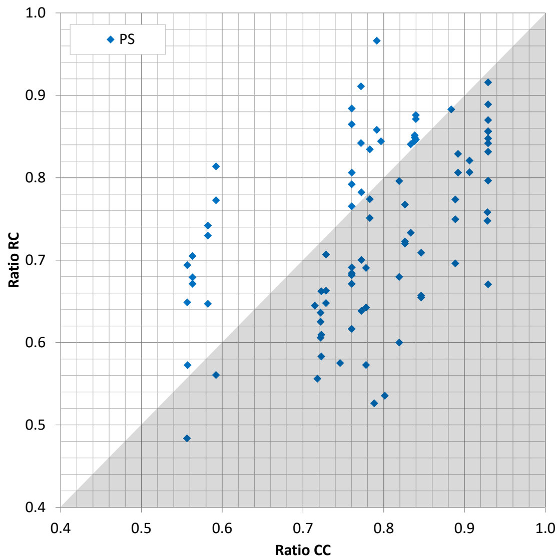


Figure IV-29. Ratio RC vs Ratio CC (PS method)

2.5.3 Adjustment of specific expressions

Lastly, as in the modulus analysis, specific expressions to predict the splitting tensile strength have been adjusted. For said purpose, the Eurocode expression has been taken as a basis, but it has been modified to introduce the replacement ratio and the recycled concrete coarse aggregate quality (considering it, again, based on its water absorption). Also in this case, a different expression has been adjusted for each of the different mixing procedures considered, and the techniques used have been multivariable regression and genetic programming.

The following general expression (Eq. 38) has been selected as a basis for the prediction of recycled splitting tensile strength using multivariable regression.

$$f_{sp,RC} = \frac{1}{3} \cdot f_{c,RC}{}^{\left[2/3 \cdot \left(1 - a \cdot \frac{\%RCA}{100}\right)\right]} \cdot \frac{\left(1 - b \cdot \frac{\%RCA}{100} \cdot \frac{WA}{5}\right)}{\left(1 - d \cdot \frac{\%RCA}{100}\right)} \tag{38}$$

Thus, the parameters *a*, *b* and *d* have been adjusted (Table IV-12) using multivariable regression.

Table IV-12. Parameters *a, b* and *d* adjusted using multivariable regression– $f_{sp,RC}$ expression

Production method	*a*	*b*	*d*
AD	-0.3372	-0.6645	-4.0387
ADwEW	-0.2662	-0.1752	-2.2450
PS	0.6545	0.1803	0.7792

In the case of genetic programming, Eq. 39 has been established to guide the search process and to be optimized using this technique.

$$f_{sp,RC} = \frac{1}{3} \cdot f_{c,RC}^{\left[2/3 \cdot \left(1 - \frac{\%RCA}{100} \cdot Branch_1\right)\right]} \cdot \left(1 - \frac{\%RCA}{100} \cdot Branch_2\right) \tag{39}$$

Where:

$Branch_1 = f\left(\frac{\%RCA}{100}, \frac{WA}{5}\right)$ and $Branch_2 = f\left(\frac{\%RCA}{100}, \frac{WA}{5}\right)$

Again, the rules for generating the branches have been as follows: both include two variables, *%RCA* and *water absorption (WA)* and the maximum number of occurrences of the variables, equal in both branches, has been restricted to 2.

Apart from these limitations, the equation has been generated by the terminal and non-terminal nodes shown in Table IV-1. At the end of the genetic programming, one final expression was obtained for each mixing procedure. The "shape" of each branch of the equation has been determined and the final results are as follows.

For the AD method (Eq. 40-41):

$$Branch_1 = \frac{0.001261 \cdot \frac{WA}{5}}{\frac{\%RCA}{100} \cdot \left(\frac{1}{\frac{WA}{5}} - 0.9568\right)} \tag{40}$$

$$Branch_2 = 0.1515 - \frac{0.1450}{\frac{WA}{5}} - \frac{0.1515 \cdot \left(\frac{WA}{5} - 3\right)}{\frac{\%RCA}{100}} \tag{41}$$

For the ADwEW method (Eq. 42-43):

$$Branch_1 = \frac{\frac{WA}{5} \cdot \left(\frac{WA}{5} - 1\right)}{28} \tag{42}$$

$$Branch_2 = \frac{2}{\frac{\%RCA}{100} \cdot \left(2 \cdot \frac{WA}{5} + 6\right)} \tag{43}$$

For the PS method (Eq. 44-45):

$$Branch_1 = \frac{\frac{WA}{5} + \frac{\%RCA}{100} - 1.5271}{\frac{\%RCA}{100} + 8} \tag{44}$$

$$Branch_2 = -\frac{0.001574 \cdot \left(\frac{0.1255}{\frac{\%RCA}{100}} + 3\right)}{\frac{\%RCA}{100} \cdot \left(\frac{WA}{5} - 1.1255\right)} \tag{45}$$

The obtained equations have been analysed comparing their behaviour with those obtained in the literature (Table IV-13, Table IV-14 and Table IV-15). Regarding the authors' expressions, the equation of Xiao et al. [XIAO06] generally shows the best adjustment. The equations obtained with multivariable regression do not manage to improve the statistical indexes of the other authors' expressions. However, with the genetic programming technique, the equations obtained always show the best statistical indexes. They show *r*, MSE, COV and MAE values better than the best ones from the literature. Furthermore, they improve the accuracy of other authors' expressions.

Table IV-13. Statistical indexes for AD method – f_{sp} expressions

AD method	Training set				Testing set			
	r	MSE	COV	MAE	*r*	MSE	COV	MAE
Multivariable	0.9155	0.1786	17.7369	0.3528	0.9557	0.1467	14.8532	0.3175
Genetic Prog	0.9497	0.0990	13.6302	0.2451	0.9606	0.0953	11.5626	0.2529
Xiao(2006)	0.9321	0.1417	15.5208	0.3010	0.9520	0.1162	13.4749	0.2841
Katz(2003	0.9322	1.1052	18.6360	0.9897	0.9485	1.1571	17.8589	1.0201
Li(2008)	0.8556	0.4164	19.6790	0.5117	0.8841	0.3701	17.1291	0.4595

Table IV-14. Statistical indexes for ADwEW method – f_{sp} expressions

ADwEW method	Training set				Testing set			
	r	MSE	COV	MAE	*r*	MSE	COV	MAE
Multivariable	0.8450	0.3022	17.0106	0.3922	0.8201	0.3585	21.4621	0.4680
Genetic Prog	0.8611	0.2461	15.3000	0.3568	0.8340	0.3054	18.9409	0.4327
Xiao(2006)	0.8631	0.3712	15.0781	0.4816	0.8230	0.3926	19.3739	0.5338
Katz(2003	0.8615	0.8436	15.7319	0.7975	0.8173	1.0188	18.7836	0.8715
Li(2008)	0.7927	1.0496	17.1365	0.9027	0.7720	0.9755	19.9632	0.8693

Table IV-15. Statistical indexes for PS method – f_{sp} expressions

PS method	Training set				Testing set			
	r	MSE	COV	MAE	*r*	MSE	COV	MAE
Multivariable	0.5761	0.2826	17.3990	0.3863	0.7940	0.2506	19.2513	0.4490
Genetic Prog	0.7844	0.5913	15.6460	0.5795	0.8556	0.2838	16.7421	0.4362
Xiao(2006)	0.7215	0.2117	14.1118	0.3777	0.8738	0.2526	16.7163	0.4165
Katz(2003	0.7303	0.9120	12.7484	0.8545	0.8733	0.8198	18.6741	0.8060
Li(2008)	0.6689	0.4084	17.9447	0.5438	0.8287	0.4725	17.0003	0.5420

Lastly, in Figure IV-30, Figure IV-31, Figure IV-32, Figure IV-33, Figure IV-34 and Figure IV-35 the "*predicted value vs experimental value*" relationship can be observed for the group of data used to adjust the equations (training set) and for the group of data used to validate them (testing set). Both relationships are shown for the equation obtained using multivariable regression and for the equation optimized using genetic programming.

As in the modulus analysis, both techniques provide an expression that can be suggested to calculate the splitting tensile strength of recycled aggregate concrete. However, the equation optimized using genetic programming has shown better statistical indexes whereas again, the equation obtained using multivariable regression is simpler.

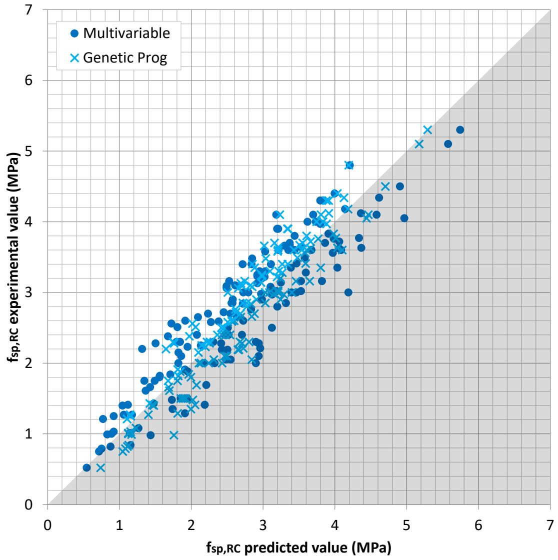


Figure IV-30. $f_{sp,RC}$ predicted value vs $f_{sp,RC}$ experimental value. Training performance (AD method)

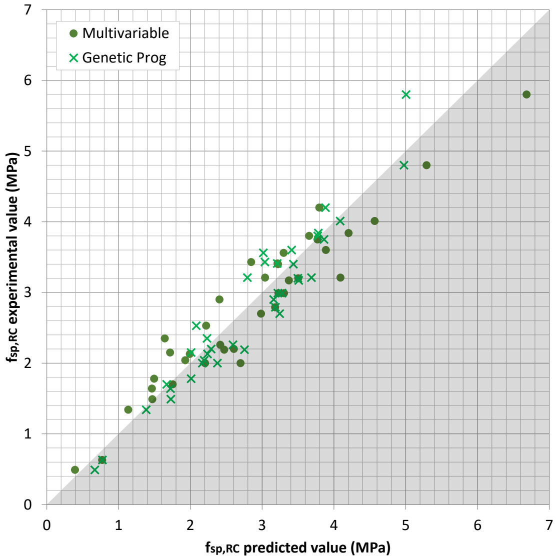


Figure IV-31. $f_{sp,RC}$ predicted value vs $f_{sp,RC}$ experimental value. Testing performance (AD method)

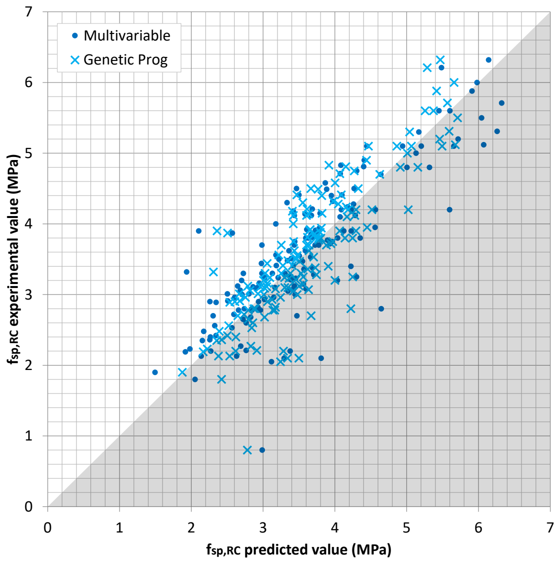


Figure IV-32. $f_{sp,RC}$ predicted value vs $f_{sp,RC}$ experimental value. Training performance (ADwEW method)

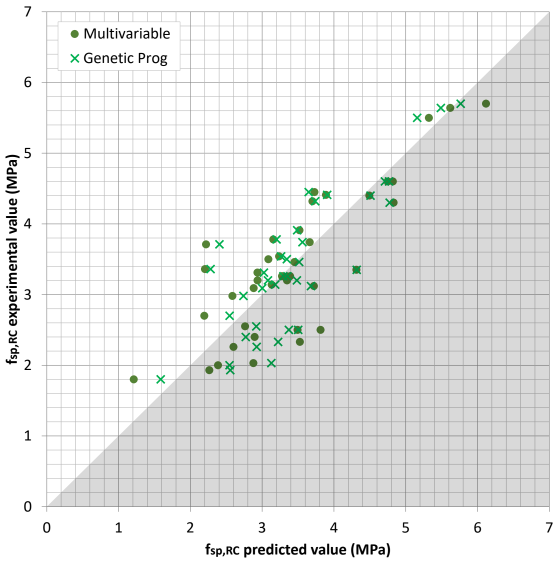


Figure IV-33. $f_{sp,RC}$ predicted value vs $f_{sp,RC}$ experimental value. Testing performance (ADwEW method)

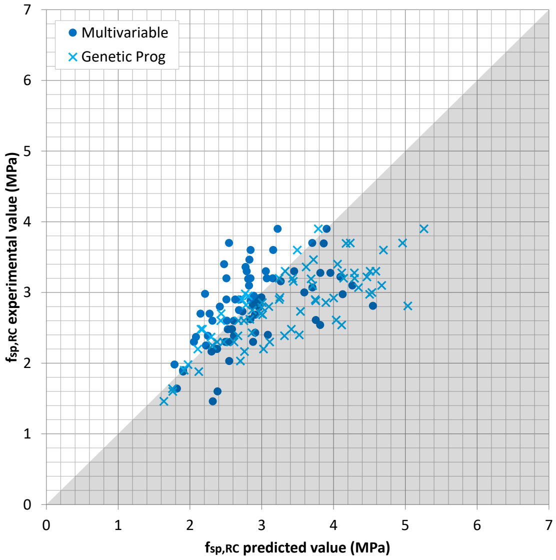


Figure IV-34. $f_{sp,RC}$ predicted value vs $f_{sp,RC}$ experimental value. Training performance (PS method)

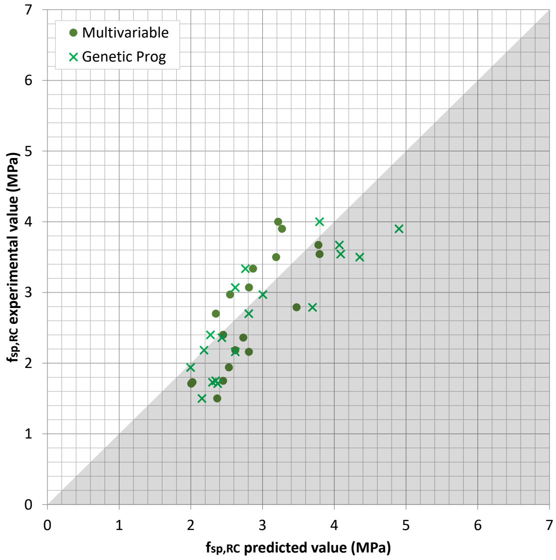


Figure IV-35. $f_{sp,RC}$ predicted value vs $f_{sp,RC}$ experimental value. Testing performance (AD method)

In Figure IV-36, the final research proposal is shown with the objective of supporting the applicability of results final research proposal.

3 SELF-COMPACTING RECYCLED CONCRETE (SCRC)

In general, compressive strength of self-compacting concrete (SCC) should be higher than that of conventional vibrated concrete, as SCC is designed with a relatively low water to cementitious materials ratio (w/cm) which is necessary to enhance resistance to segregation [KHAY08].

Even at the same w/cm, properly designed SCC can exhibit higher compressive strength than conventional vibrated concrete due to the incorporation of supplementary cementitious materials and fillers, which can serve as nucleation sites and refine the porosity of the cement paste. In fact, limestone powder, a commonly used addition in SCC, contributes significantly to strength at ages up to at least 28 days [DOMO07].

Regarding the modulus of elasticity of SCC, it can be in reasonable agreement with the elastic stiffness assumed during the design of conventional slump concrete structures [KOVL11].

However, it is also reported that for some SCC mixtures, the modulus of elasticity may be 80% of that typically found in high-performance concrete of normal consistency [KHAY08]. The modulus of elasticity of the parent rock and the relative volume of the aggregate in the concrete mixture has significant influence on the modulus of elasticity of the concrete. In addition to the total aggregate volume, adjustments of the sand-to-aggregate ratio can also influence the elastic modulus of SCC. Spread of up to 20% could be obtained compared to the modulus of elasticity of vibrated high-performance concrete due to the lower coarse aggregate volume of SCC. However, under air-drying curing conditions, the elastic modulus of SCC can be higher than that of conventional vibrated concrete in the long term. These results can be attributed to the lower loss of water that may occur in the case of SCC.

Proposal

AD

$$E_{c,RC} = 22000 \cdot \left(\frac{f_{c,RC}}{10}\right)^{\left[0.3\cdot\left(1+0.6378\cdot\frac{\%RCA}{100}\right)\right]} \cdot \frac{\left(1 + 0.4449 \cdot \frac{\%RCA}{100} \cdot \frac{WA}{5}\right)}{\left(1 + 1.4893 \cdot \frac{\%RCA}{100}\right)}$$

$$f_{sp,RC} = \frac{1}{3} \cdot f_{c,RC}^{\left[{}^{2}/_{3}\cdot\left(1-\frac{\%RCA}{100}\cdot\frac{0.001261\cdot\frac{WA}{5}}{\frac{\%RCA}{100}\cdot\left(\frac{1}{\frac{WA}{5}}-0.9568\right)}\right)\right]} \cdot \left[1 - \frac{\%RCA}{100} \cdot \left(0.1515 - \frac{0.1450}{\frac{WA}{5}} - \frac{0.1515 \cdot \left(\frac{WA}{5} - 3\right)}{\frac{\%RCA}{100}}\right)\right]$$

Recommended method: ADwEW

$$E_{c,RC} = 22000 \cdot \left(\frac{f_{c,RC}}{10}\right)^{\left[0.3\cdot\left(1+0.7539\cdot\frac{\%RCA}{100}\right)\right]} \cdot \frac{\left(1 + 0.1403 \cdot \frac{\%RCA}{100} \cdot \frac{WA}{5}\right)}{\left(1 + 1.0534 \cdot \frac{\%RCA}{100}\right)}$$

$$f_{sp,RC} = \frac{1}{3} \cdot f_{c,RC}^{\left[{}^{2}/_{3}\cdot\left(1-\frac{\%RCA}{100}\cdot\frac{\frac{WA}{5}\cdot\left(\frac{WA}{5}-1\right)}{28}\right)\right]} \cdot \left[1 - \frac{\%RCA}{100} \cdot \frac{2}{\frac{\%RCA}{100}\cdot\left(2\cdot\frac{WA}{5}+6\right)}\right]$$

PS

$$E_{c,RC} = 22000 \cdot \left(\frac{f_{c,RC}}{10}\right)^{\left[0.3\cdot\left(1+0.4143\cdot\frac{\%RCA}{100}\right)\right]} \cdot \frac{\left(1 - 0.1636 \cdot \frac{\%RCA}{100} \cdot \frac{WA}{5}\right)}{\left(1 + 0.2700 \cdot \frac{\%RCA}{100}\right)}$$

$$f_{sp,RC} = \frac{1}{3} \cdot f_{c,RC}^{\left[{}^{2}/_{3}\cdot\left(1-\frac{\%RCA}{100}\cdot\frac{\frac{WA}{5}+\frac{\%RCA}{100}-1.5271}{\frac{\%RCA}{100}+8}\right)\right]} \cdot \left[1 - \frac{\%RCA}{100} \cdot \left(-\frac{0.001574\cdot\left(\frac{0.1255}{\frac{\%RCA}{100}}+3\right)}{\frac{\%RCA}{100}\cdot\left(\frac{WA}{5}-1.1255\right)}\right)\right]$$

Figure IV-36. Final research proposal

Domone [DOMO07] concluded that the elastic modulus of SCC can be up 40% lower than that of normal vibrated concrete at low compressive strength, but the difference can be reduced to less than 5% at high strengths. This behaviour is consistent with the lower coarse aggregate quantities in SCC.

Regarding splitting tensile strength, the common use of supplementary cementitious materials (and in some cases fillers) and the high content of ultra-fine materials, can contribute to the densification of the cement matrix and the reduction of the extent of interfacial transition zone with the aggregate. These parameters are of significant importance when the tensile load bearing behaviour is analysed. Therefore, it was reported that higher tensile strength values can be obtained with SCC compared to those with conventional vibrated concrete [KHAY08].

On the other hand, some authors state that, in general, no significant difference can be observed between the splitting tensile strength of SCC and vibrated concrete [KOVL11]. Moreover, the ratio of splitting tensile strength to compressive strength for SCC is similar to that of conventional vibrated concrete [DOMO07].

Finally, some authors stated that code expressions predict a higher modulus of elasticity than that experimentally obtained [KHAY08]. However, in spite of this fact, it is accepted that code expressions used with vibrated concrete can be used with SCC. So, as aforementioned, this means that hardened-state behaviour of self-compacting recycled concrete (SCRC) can be predicted using equations developed with vibrated recycled concrete.

Then, in this last section, the results obtained with vibrated recycled concrete have been used to predict the behaviour of self-compacting recycled concrete and the accuracy of these predictions are analysed when this concrete is used.

3.1 Objectives

The analysis carried out in section 2 states that compressive strength, modulus of elasticity and splitting tensile strength of recycled concrete decrease as the percentage of recycled concrete coarse aggregate increases. These reductions are mainly due to the weak interface (ITZ) between the recycled aggregate and new cement paste. The properties of this ITZ depend on different features, the two most significant of which are the quality of recycled aggregate and also the mixing procedure. Therefore, different adjustments have been proposed to predict the basic mechanical properties of structural recycled concrete, taking into account, not only the recycled percentage and quality of the recycled aggregates used, but also the production method. Furthermore, this part of the work concludes with the proposal of simple expressions which allow engineers to estimate properties of recycled concrete similarly to those used for conventional concrete.

Moreover, although some authors state that mechanical properties of SCC are different from those obtained with vibrated concrete, they conclude that code expressions regarding vibrated concrete can be used with SCC.

Therefore, the next objective of this part of the study is to prove that the adjustments obtained with vibrated recycled concrete in section 2 can be applied accurately when analysing the behaviour of self-compacting recycled concrete. This will demonstrate that the mechanical properties (compressive strength, modulus of elasticity and splitting tensile strength) of SCRC are affected by the incorporation of recycled aggregates to a similar extent as those of vibrated recycled concrete.

The methodology used to reach this objective is the same as that described in section 2.

Firstly, as explained in section 2.2.2, the experimental results obtained were used to compare the mechanical properties of the control self-compacting concrete (SCC) with those of different self-compacting recycled concretes (SCRC) made with the same dosage and materials, except for the coarse aggregate, which was replaced with recycled concrete coarse aggregate (by volume) at different percentages. With the experimental results obtained, and using linear regression, a coefficient was adjusted which allows the estimation of the SCRC property as a function of that of SCC. This coefficient takes into account the recycled content and the mixing procedure used. Once obtained, the coefficients were compared with those obtained with vibrated concretes in section 2.

Secondly, code predictions (some of them adjusted specifically for SCC) were analysed to observe that they are not able to predict SCRC properties with the same approximation degree as in SCC, as it occurs with vibrated concretes. So, the correction coefficients adjusted with vibrated concretes and obtained according to the methodology described in section 2.2.3 were used. The new predictions were analysed and the suitability of the correction coefficients when SCRC is used was evaluated.

Lastly, the specific expressions adjusted with vibrated recycled concrete according to section 2.2.4 have been used to predict SCRC properties (modulus of elasticity and splitting tensile strength). As aforementioned, although some authors state that the mechanical properties of SCC are quite different from those obtained with vibrated concrete, they conclude that code expressions regarding vibrated concrete can be used with SCC. So, in this case, the suitability of the specific expressions adjusted with vibrated recycled concrete was analysed, comparing their predictions with those obtained using the expressions proposed by the codes (that is the expressions used with vibrated conventional concrete).

3.2 Hardened properties of SCRC

To fully assess this part of the work, the hardened-state behaviour of SCRC has to be thoroughly analysed. To do so, nine cubic specimens of 100 x 100 x 100 mm for each mix were used in the “Rheology” and “Robustness” working phases in order to determine the density (EN 12390-7) [EN12390-7]. The compressive strength was measured with another nine cubic specimens of 100 x 100 x 100 mm for each mix which were tested at three testing ages (three specimens at each age): 3, 7 and 28 days (EN 12390-3) [EN12390-3]. In the “Thixotropy” working phase three cylindrical specimens of 150 x 300 mm were also made to determine the compressive strength (EN 12390-3). They were all tested at 28 days. In addition, the modulus of elasticity and the splitting tensile strength were also measured at 28 days, each property with three cylindrical specimens of 150 x 300 mm, using EN 12390-13 and EN 12390-6 standards, respectively [EN12390-13, EN12390-6].

As described in Chapter III, two mixing procedures were used in the “Rheology” phase: “air-dry with extra-water-ADwEW” (both M1 and M3 methods) and “pre-soaked-PS” (M2 method). In the “Robustness” phase only the “air-dry with extra-water-ADwEW” mixing procedure was used (both M1 and M3 methods). Also, in the “Thixotropy” phase only the “air-dry with extra-water-ADwEW” mixing procedure was used (M1 method).

3.2.1 Density

The density in fresh-state was obtained according to EN 12350-6 [EN12350-6]. The SCRC values were between 2.29 and 2.40 t/m³ (Table IV-16 and Table IV-17). These values are in agreement with the common range for fresh density values of vibrated recycled concretes (between 2.13 and 2.40 t/m³ [ACHE06, JUAN04, GONZ02]).

The density of hardened SCRC was evaluated one day after the concrete cubes were demoulded according to EN 12390-7 [EN12390-7]. The density values obtained (between 2.34 and 2.47 t/m³) display, as in fresh-state density, a decrease as the replacement ratio of recycled coarse aggregate increases (Table IV-16 and Table IV-17). The values obtained are, also, in agreement with those corresponding to vibrated recycled concrete.

The SCRC density in both hardened and fresh states is lower than that of conventional SCC, due to the lower density of recycled aggregate. This lower aggregate density is due to the adhered mortar of recycled coarse aggregates.

Table IV-16. Results of SCRC density (“Rheology” phase)

Mix	Fresh-state density (t/m³)	Hardened-state density (t/m³)
0	2.41	2.49
20M1	2.40	2.45
50M1	2.39	2.43
100M1	2.35	2.39
20M2	2.38	2.46
50M2	2.37	2.44
100M2	2.30	2.36
20M3	2.41	2.47
50M3	2.40	2.45
100M3	2.32	2.38

Table IV-17. Results of SCRC density ("Robustness" phase)

Mix	Fresh-state density (t/m³)						Hardened-state density (t/m³)					
	W+	W-	S+	S-	C+	C-	W+	W-	S+	S-	C+	C-
0	2.41	2.42	2.40	2.40	2.46	2.40	2.48	2.50	2.47	2.47	2.50	2.47
20M1	2.39	2.39	2.40	2.37	2.34	2.39	2.46	2.47	2.47	2.45	2.45	2.45
50M1	2.35	2.36	2.37	2.36	2.34	2.34	2.43	2.44	2.44	2.42	2.40	2.40
100M1	2.32	2.34	2.30	2.31	2.31	2.29	2.38	2.40	2.37	2.36	2.35	2.34
20M3	2.41	2.40	2.39	2.39	2.42	2.40	2.47	2.47	2.47	2.46	2.47	2.46
50M3	2.37	2.38	2.36	2.37	2.37	2.37	2.43	2.43	2.43	2.42	2.44	2.43
100M3	2.32	2.36	2.32	2.34	2.34	2.32	2.37	2.40	2.37	2.39	2.40	2.37

According to Figure IV-37 and regarding the fresh-state density of the reference concrete, the reductions obtained were between 0.47% and 1.24% for 20% RCA, between 1.62% and 1.97% for 50% RCA, and between 3.41% and 4.62% for 100% RCA.

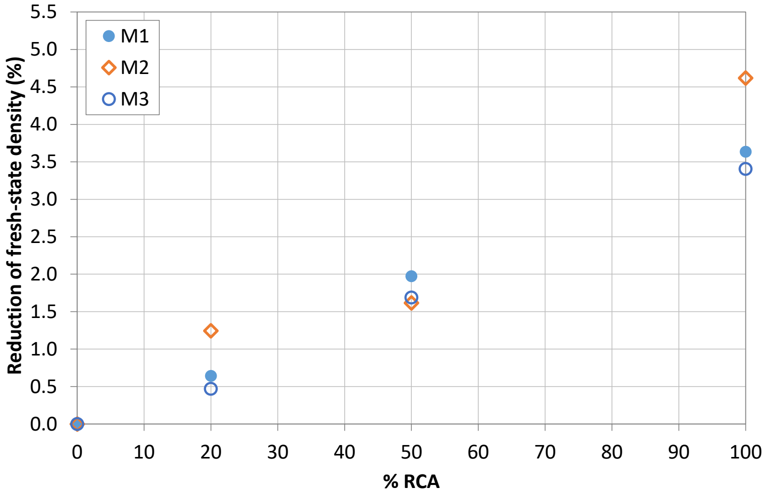


Figure IV-37. Reduction of SCRC fresh-state density vs recycled coarse aggregate percentage

Now, according to Figure IV-38 and regarding the hardened-state density of the reference concrete, the reductions obtained were between 0.60% and 1.27% for 20% RCA, between 1.98% and 2.35% for 50% RCA, and between 3.97% and 4.96% for 100% RCA.

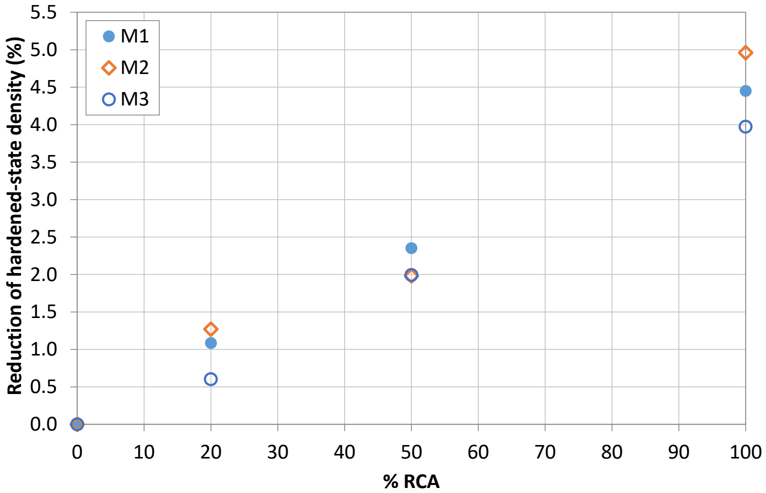


Figure IV-38. Reduction of SCRC hardened-state density vs recycled coarse aggregate percentage

These reductions are in the same range as those of vibrated recycled concretes: 1% to 5% when the recycled coarse aggregate percentage is lower than 50% and 4% to 15% when 100% replacement is used [SEAR16, BRIT16, ETXE07b, ACHE06].

Thus, it can be concluded that the effect of the incorporation of recycled coarse aggregate on SCC density is similar to its effect on vibrated concrete. Consequently, as some authors reported in their researches about vibrated recycled concrete [SEAR15], SCRC shows lower fresh and hardened density than conventional SCC, mainly due to the adhered mortar of recycled coarse aggregates.

3.2.2 Mechanical properties

Table IV-18, Table IV-19 and

Table IV-20 list the basic properties of hardened self-compacting recycled concrete: cube compressive strength ("Rheology" and "Robustness" phases), cylinder compressive strength, modulus of elasticity and splitting tensile strength ("Thixotropy" phase).

Table IV-18. Results of SCRC mechanical properties ("Rheology" phase)

Mix	$f_{c,cub,3}$ (MPa)	$f_{c,cub,7}$ (MPa)	$f_{c,cub,28}$ (MPa)
0	68.3	73.8	80.4
20M1	64.2	70.2	76.9
50M1	64.2	68.1	75.5
100M1	59.9	64.2	70.5
20M2	64.8	71.5	77.8
50M2	62.1	66.7	72.4
100M2	54.9	61.6	66.4
20M3	66.8	70.9	79.0
50M3	64.8	69.5	75.9
100M3	60.0	65.3	69.3

Table IV-19. Results of SCRC mechanical properties ("Robustness" phase)

Mix	W+			W-			S+			S-			C+			C-		
	$f_{c,3}$	$f_{c,7}$	$f_{c,28}$	$f_{c,3}$	$f_{c,7}$	$f_{c,28}$	$f_{c,3}$	$f_{c,7}$	$f_{c,28}$	$f_{c,3}$	$f_{c,7}$	$f_{c,28}$	$f_{c,3}$	$f_{c,7}$	$f_{c,28}$	$f_{c,3}$	$f_{c,7}$	$f_{c,28}$
0	67.2	73.2	79.6	68.6	74.9	80.8	67.0	73.9	81.5	66.6	73.7	80.8	69.8	75.7	80.6	66.2	71.4	79.8
20M1	64.8	70.2	75.5	66.5	74.4	80.5	68.5	72.3	79.3	64.9	70.1	76.9	65.1	71.1	78.5	63.7	70.9	76.7
50M1	63.8	67.9	73.6	64.5	68.1	76.3	66.5	70.2	76.2	63.7	67.6	73.6	60.8	67.6	73.8	60.5	62.2	69.5
100M1	59.5	64.9	70.0	60.6	66.6	70.4	58.3	62.2	69.4	59.5	63.8	70.4	56.8	62.0	67.0	55.1	59.3	63.9
20M3	66.3	70.7	79.0	66.9	71.4	80.8	69.7	73.5	81.0	67.0	72.4	78.6	69.1	73.3	80.6	66.5	70.8	79.5
50M3	63.9	69.3	74.2	64.9	69.2	76.1	66.1	71.4	76.1	62.9	68.6	72.2	65.7	70.0	76.6	62.2	68.4	73.5
100M3	59.1	61.6	69.3	63.1	67.5	72.0	58.5	63.3	69.0	60.2	65.6	69.9	63.0	67.9	74.5	57.3	60.8	66.1

Table IV-20. Results of SCRC mechanical properties ("Thixotropy" phase)

Mix	f_c (MPa)	E_c (MPa)	f_{sp} (MPa)
0	54.8	30200	4.55
20M1	50.2	27400	4.20
50M1	49.6	26500	4.10
100M1	48.5	25600	4.00

In general terms, regarding mechanical strengths, as in vibrated recycled concrete, SCRC compressive and splitting tensile strengths decrease when the content of recycled aggregate increases. The results also state that, as with mechanical strengths, the modulus of elasticity is affected by the use of recycled coarse aggregate. This property decreases when the replacement percentage increases, as is well studied in vibrated RC.

3.3 SCC property vs SCRC property

The coefficients to estimate the mechanical properties of SCRC as a function of those of conventional SCC were calculated. These coefficients are shown in Table IV-21, Table IV-22 and Table IV-23. In this section, they are compared with those obtained with vibrated concretes to confirm their similarity, which indicates that the mechanical properties (compressive strength, modulus of elasticity and splitting tensile strength) of SCRC are affected by the incorporation of recycled aggregates to a similar extent as those of vibrated recycled concrete.

The coefficients were obtained using results from the three different phases, “Rheology” (Table IV-21), “Robustness” (Table IV-22) and “Thixotropy” (Table IV-23).

Table IV-21. Correction coefficients to estimate $f_{c,SCRC}$ (“Rheology” phase)

Mix	$f_{c,SCRC,3}/f_{c,SCC,3}$	$f_{c,SCRC,7}/f_{c,SCC,7}$	$f_{c,SCRC,28}/f_{c,SCC,28}$
20M1	0.940	0.951	0.956
50M1	0.940	0.923	0.939
100M1	0.877	0.870	0.877
20M2	0.949	0.969	0.968
50M2	0.909	0.904	0.900
100M2	0.804	0.835	0.826
20M3	0.978	0.961	0.983
50M3	0.949	0.942	0.944
100M3	0.878	0.885	0.862

Table IV-22. Correction coefficients to estimate $f_{c,SCRC}$ (“Robustness” phase)

Mix	W+			W-			S+			S-			C+			C-		
	3	7	28	3	7	28	3	7	28	3	7	28	3	7	28	3	7	28
20M1	0.97	0.96	0.95	0.97	0.99	1.00	1.02	0.98	0.97	0.97	0.95	0.95	0.93	0.94	0.97	0.96	0.99	0.96
50M1	0.95	0.93	0.92	0.94	0.91	0.94	0.99	0.95	0.93	0.96	0.92	0.91	0.87	0.89	0.92	0.91	0.87	0.87
100M1	0.89	0.89	0.88	0.88	0.89	0.87	0.87	0.84	0.85	0.89	0.87	0.87	0.81	0.82	0.83	0.83	0.83	0.80
20M3	0.99	0.97	0.99	0.97	0.95	1.00	1.04	1.00	0.99	1.01	0.98	0.97	0.99	0.97	1.00	1.01	0.99	1.00
50M3	0.95	0.95	0.93	0.95	0.92	0.94	0.99	0.97	0.93	0.94	0.93	0.89	0.94	0.92	0.95	0.94	0.96	0.92
100M3	0.88	0.84	0.87	0.92	0.90	0.89	0.87	0.86	0.85	0.90	0.89	0.87	0.90	0.90	0.92	0.87	0.85	0.83

Table IV-23. Correction coefficients to estimate $f_{c,SCRC}$, $E_{c,SCRC}$, $f_{sp,SCRC}$ (“Thixotropy” phase)

Mix	$f_{c,SCRC}/f_{c,SCC}$	$E_{c,SCRC}/E_{c,SCC}$	$f_{sp,SCRC}/f_{sp,SCC}$
20M1	0.916	0.907	0.923
50M1	0.905	0.877	0.901
100M1	0.885	0.848	0.879

3.3.1 Compressive strength (f_c)

Figure IV-39, Figure IV-40, Figure IV-41, Figure IV-42, Figure IV-43 and Figure IV-44 show the “recycled concrete compressive strength vs conventional concrete compressive strength” relationship for the different recycled percentages and different production methods obtained in section 2.3. Some red points have been included in the following figures. They represent the values obtained with SCRC (Table IV-21, Table IV-22 and Table IV-23) for the different phases.

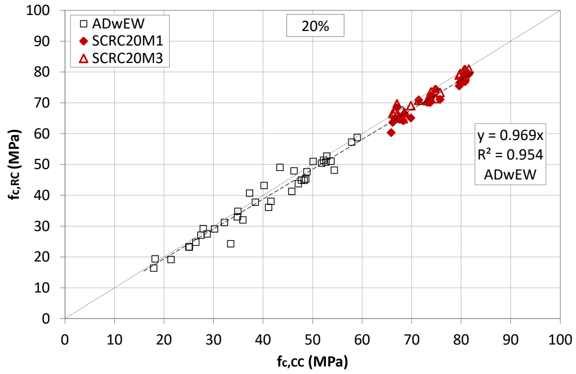


Figure IV-39. $f_{c,RC}$ **vs** $f_{c,CC}$ **;** $f_{c,SCRC}$ **vs** $f_{c,SCC}$ **(20%-ADwEW)**

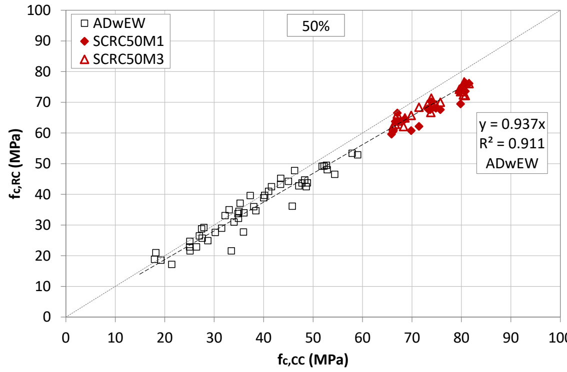


Figure IV-40. $f_{c,RC}$ **vs** $f_{c,CC}$ **;** $f_{c,SCRC}$ **vs** $f_{c,SCC}$ **(50%-ADwEW)**

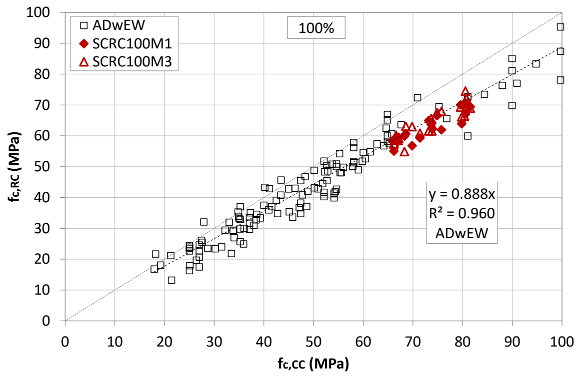


Figure IV-41. $f_{c,RC}$ **vs** $f_{c,CC}$ **;** $f_{c,SCRC}$ **vs** $f_{c,SCC}$ **(100%-ADwEW)**

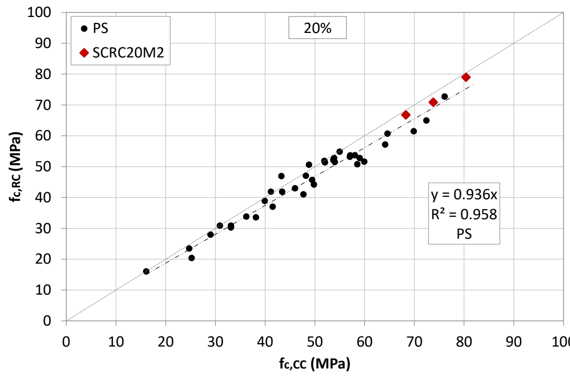


Figure IV-42. $f_{c,RC}$ **vs** $f_{c,CC}$ **;** $f_{c,SCRC}$ **vs** $f_{c,SCC}$ **(20%-PS)**

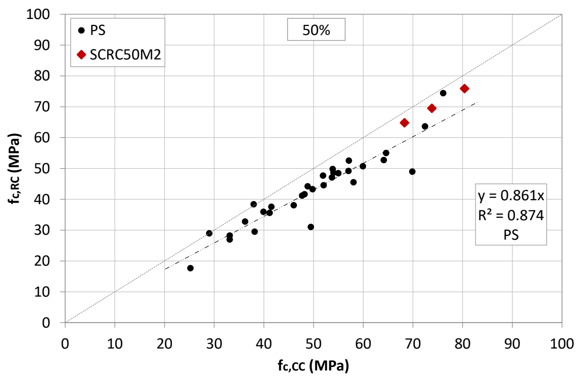


Figure IV-43. $f_{c,RC}$ **vs** $f_{c,CC}$ **;** $f_{c,SCRC}$ **vs** $f_{c,SCC}$ **(50%-PS)**

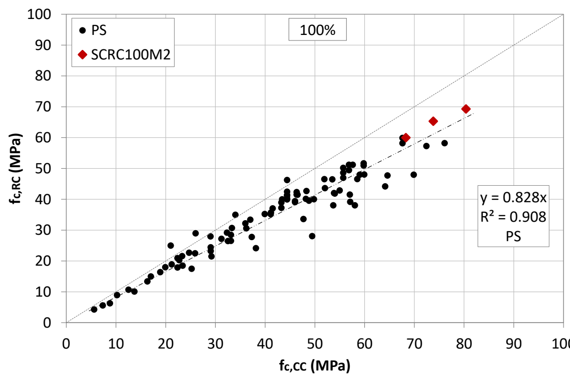


Figure IV-44. $f_{c,RC}$ **vs** $f_{c,CC}$ **;** $f_{c,SCRC}$ **vs** $f_{c,SCC}$ **(100%-PS)**

It can be seen that the red points are perfectly aligned with the straight lines obtained in section 2.3 using linear regression with the database of vibrated recycled concrete. Therefore, this confirms that, regarding compressive strength, the incorporation of recycled concrete coarse aggregate affects SCC to a similar extent as with vibrated concrete. The reduction in SCRC compressive strength depends on the percentage of recycled aggregate and the mixing procedure used and is similar to that experienced with recycled vibrated concretes.

3.3.2 Modulus of elasticity (E_c)

The same analysis for compressive strength has been carried out for the modulus of elasticity. Using the relationships previously obtained with the vibrated recycled concrete database, new red points have been included in Figure IV-45 and Figure IV-46. They show SCRC behaviour regarding the modulus of elasticity for the different replacement percentages (Table IV-23). Again, it can be seen that the points are perfectly aligned with the straight lines obtained in section 2.4.1 using linear regression with the database of vibrated recycled concrete.

Therefore, as with compressive strength, it can be stated that the incorporation of recycled concrete coarse aggregate affects the modulus of elasticity of SCC, to the same extent as the modulus of elasticity of vibrated concrete.

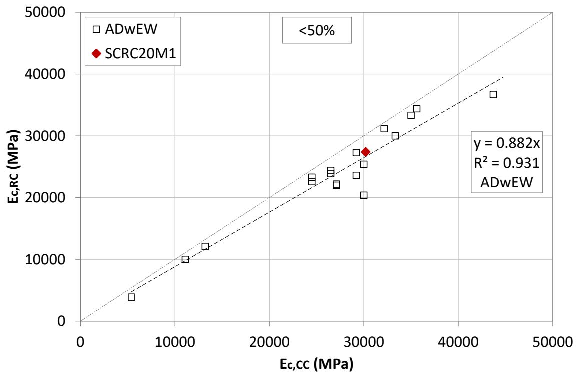


Figure IV-45. $E_{c,RC}$ vs $E_{c,CC}$; $E_{c,SCRC}$ vs $E_{c,SCC}$ (<50%)

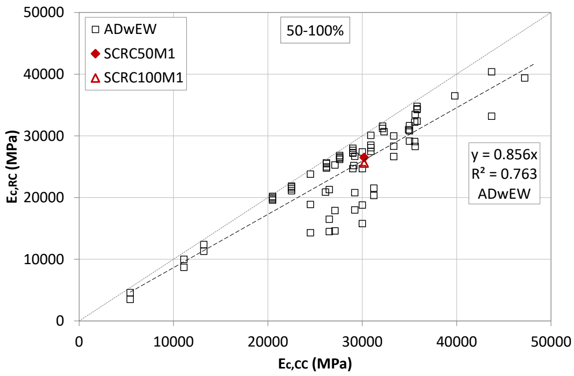


Figure IV-46. $E_{c,RC}$ vs $E_{c,CC}$; $E_{c,SCRC}$ vs $E_{c,SCC}$ (50-100%)

3.3.3 Splitting tensile strength (f_{sp})

Finally, the same analysis as for compressive strength and modulus of elasticity has been carried out for splitting tensile strength. Using the relationships previously obtained with the recycled vibrated concrete database, new red points have been included in Figure IV-47 and Figure IV-48. They show SCRC behaviour regarding splitting tensile strength for the different replacement percentages (Table IV-23). Again, it can be seen that the points are perfectly aligned with the straight lines obtained in section 2.5.1 using linear regression with the database of vibrated recycled concrete.

This confirms that, regarding splitting tensile strength, the incorporation of recycled concrete coarse aggregate affects SCC to a similar extent as vibrated concrete.

3.4 Suitability of correction coefficients to code expressions

As aforementioned, the prediction expressions proposed in codes to estimate the modulus of elasticity and the splitting tensile were analysed. To do so, the code predictions were compared with the experimental results using the *"experimental property/calculated property"* ratios. It should be noted that, as in section 2, the calculated values were obtained using the experimental compressive strength of concretes.

As in section 2, in order to assess the suitability of code expressions when SCRC is used, the *"experimental property/calculated property"* ratios obtained with SCC were compared with those obtained with SCRC. If these ratios are similar, it can be considered that code expressions used with SCRC provide the same approximation degree as those of conventional SCC, and hence, they do not need to be corrected. Nevertheless, if the ratio decreases as the percentage of recycled aggregate increases, it will be necessary to correct the code expressions.

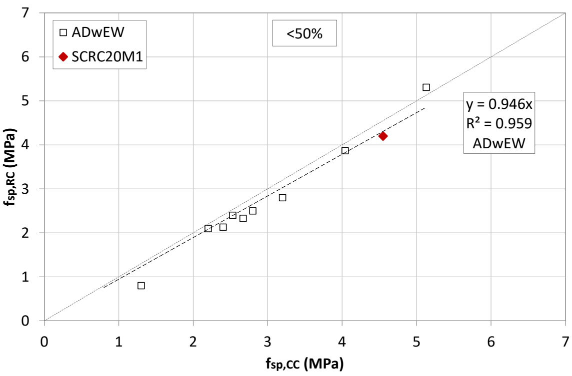


Figure IV-47. $f_{sp,RC}$ **vs** $f_{sp,CC}$ **;** $f_{sp,SCRC}$ **vs** $f_{sp,SCC}$ **(<50%)**

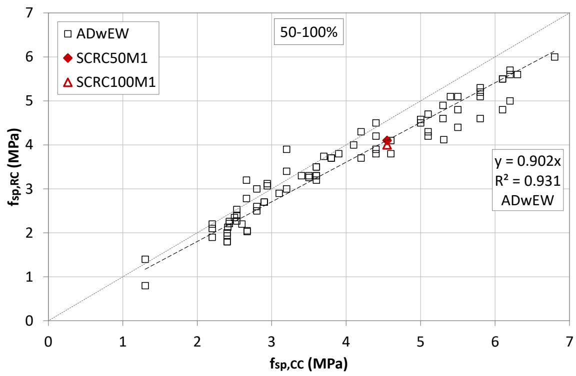


Figure IV-48. $f_{sp,RC}$ **vs** $f_{sp,CC}$ **;** $f_{sp,SCRC}$ **vs** $f_{sp,SCC}$ **(50-100%)**

However, as also aforementioned, it is expected that code expressions are not able to predict SCRC properties with the same approximation degree as in SCC, as it occurs with vibrated concretes. So, once this issue was confirmed, the correction coefficients adjusted with vibrated concretes and obtained according to the methodology described in sub-section 2.2.3 were used and with them new predictions were obtained. These new predictions were analysed and the suitability of the correction coefficients when SCRC is used was evaluated.

3.4.1 Modulus of elasticity (E_c)

Firstly, the need to adapt the code expressions to predict the modulus of elasticity of SCRC, in order to achieve the same approximation degree as that obtained in conventional SCC is analysed. For said propose, the "*experimental modulus/calculated modulus*" ratios in conventional and recycled self-compacting concretes were compared. The predictions were made according to the proposal of Eurocode [EURO04].

As can be observed in Figure IV-49, the SCC ratio is higher than those obtained with SCRC mixes and it decreases as the replacement percentage of recycled coarse aggregate increases. This means that the code expression does not provide the same approximation degree in SCRC as in SCC when calculating modulus of elasticity. Consequently, it will be necessary to modify the expression by introducing a correction coefficient.

Secondly, the correction coefficient (Eq. 46) that was adjusted by multivariable regression with the vibrated RC database (section 2.4.2) was considered.

$$CF_{ADwEW} = \frac{\left(1-0.0677\cdot\frac{\%RCA}{100}\cdot\frac{WA}{5}\right)}{\left(\frac{f_{c,RC}}{10}\right)^{\left(0.3\cdot(-0.0697)\cdot\frac{\%RCA}{100}\right)}\cdot\left(1+0.1044\cdot\frac{\%RCA}{100}\right)} \tag{46}$$

With this coefficient, the new "*experimental modulus/calculated modulus*" ratios were calculated and, as seen in Figure IV-49, the new ratios obtained with SCRC are similar to those of SCC. This means that the proposed correction coefficient allows the Eurocode expression to be used to calculate the SCRC modulus of elasticity with the same approximation degree as that of conventional SCC.

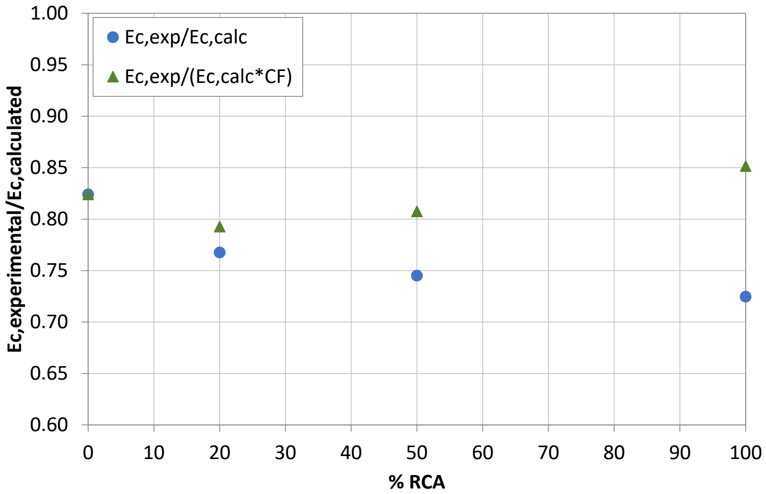


Figure IV-49. $E_{c,experimental}/E_{c,calculated\text{-}Eurocode}$ in SCRC mixes

Once this fact was confirmed, the next step consisted of analysing the modulus predictions obtained with different modified code expressions specifically adapted to SCC [KHAY08]. It is known that, when conventional SCC is studied, code expressions predict a higher modulus of elasticity than that experimentally obtained. Therefore, some authors [KHAY08] have proposed modified expressions (Eq. 47-50) that aim to improve the accuracy of the SCC modulus prediction. Although these new models are suggested for SCC, they continue to overestimate the experimentally obtained modulus values.

$$Ec_{AASHTO\ 2007\ (suggested)} = \gamma_c^{1.5} \cdot 45 \cdot (fc)^{0.5} \quad (47)$$

$$Ec_{CEB-FIP\ MC\ 90\ (suggested)} = 1.6 \cdot (fc + 8)^{0.77} \quad (48)$$

$$Ec_{ACI\ 363-92\ (suggested)} = 5.08 \cdot (fc)^{0.5} + 0.64 \quad (49)$$

$$Ec_{ACI\ 318-99\ (suggested)} = 5.18 \cdot (fc)^{0.5} \quad (50)$$

Where:

E_c = elastic modulus of concrete (GPa)

γ_c = unit weight of concrete (kg/m³)

f_c = compressive strength of concrete (MPa)

The same analysis as with the Eurocode expression was carried out for the suggested SCC expressions, i.e. the "*experimental modulus/calculated modulus*" ratios in conventional SCC and self-compacting recycled concretes were compared. Figure IV-50 shows the ratios for the different recycled percentages and for the "air-dry with extra-water-ADwEW" method obtained in section 2.4.2 with vibrated recycled concrete. Now, new points have been included in this figure. They represent the new ratios obtained with SCRC versus SCC using Eurocode and the suggested expressions. Again, in this case, the ratios of conventional SCC are higher than those obtained with SCRC (Figure IV-50), to a similar extent as the ratios of conventional concrete are higher than those of vibrated recycled concrete. This means that the suggested expressions will not provide the same approximation degree in SCC as in SCRC when calculating the modulus. Therefore, it is necessary to modify them by introducing a correction coefficient.

Results obtained by applying the correction coefficient obtained in section 2.4.2 to SCRC predictions are shown in Figure IV-51, where points regarding SCRC are added to those of vibrated recycled concrete. This figure shows the new "*experimental modulus/calculated modulus*" ratios of recycled vs conventional self-compacting concretes. As can be observed, at this stage, the ratios of SCRCs are similar to those obtained with conventional SCC and the relationship between SCRC vs SCC ratios and vibrated recycled concrete vs conventional concrete ratios is also similar.

It should be noted that the ASSHTO 2007 expression (Eq. 47) provides a SCRC ratio which is slightly higher than the general trend (Figure IV-51). This is due to the fact that it takes concrete density into account. Then, in this regard the effect of recycled aggregate incorporation is already being considered, due to the fact that the density of recycled concrete decreases as the replacement percentage increases. As correction coefficients have been adjusted to be applied to equations where this term does not exist, the results obtained with this equation can be expected to be slightly higher, especially when high replacement percentages are used.

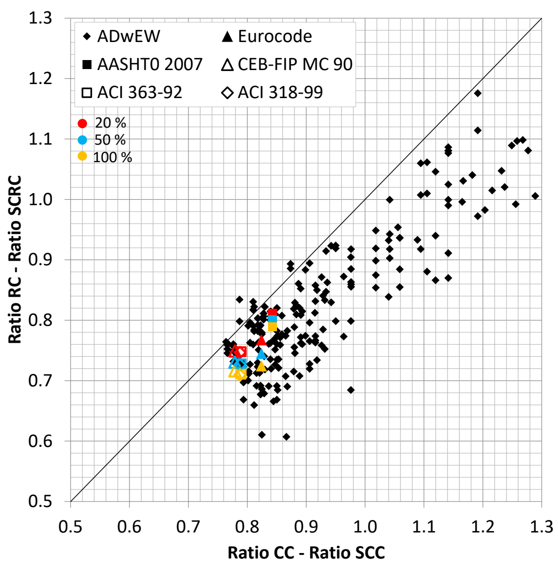


Figure IV-50. Ratio RC vs Ratio CC. Ratio SCRC vs Ratio SCC (E_c)

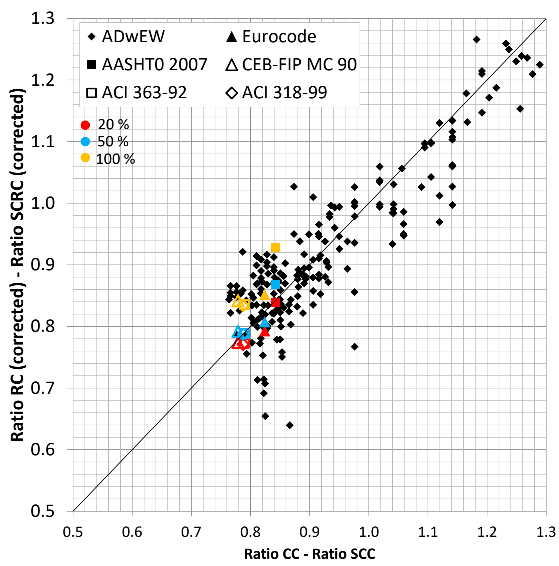


Figure IV-51. Ratio RC corrected with CF vs Ratio CC. Ratio SCRC corrected with CF vs Ratio SCC (E_c)

However, in conclusion, it can be stated that the correction coefficient obtained with RC can be used to predict the SCRC modulus providing the same approximation degree as that obtained with SCC. This means, again, that regarding the modulus of elasticity, the incorporation of recycled concrete coarse aggregate affects SCC to a similar extent as vibrated concrete.

3.4.2 Splitting tensile strength (f_{sp})

The same analysis as with the modulus of elasticity has been carried out with splitting tensile strength. Therefore, this property was calculated using the Eurocode expression [EURO04] and the predicted values were compared with those experimentally obtained using the "*experimental splitting tensile strength/calculated splitting tensile strength*" ratio.

As can be observed in Figure IV-52, the SCC ratio is similar to those obtained with SCRC mixes. This means that code expressions provide the same approximation degree in SCRC as in SCC when calculating splitting tensile strength. Consequently, it will not be necessary to modify this expression.

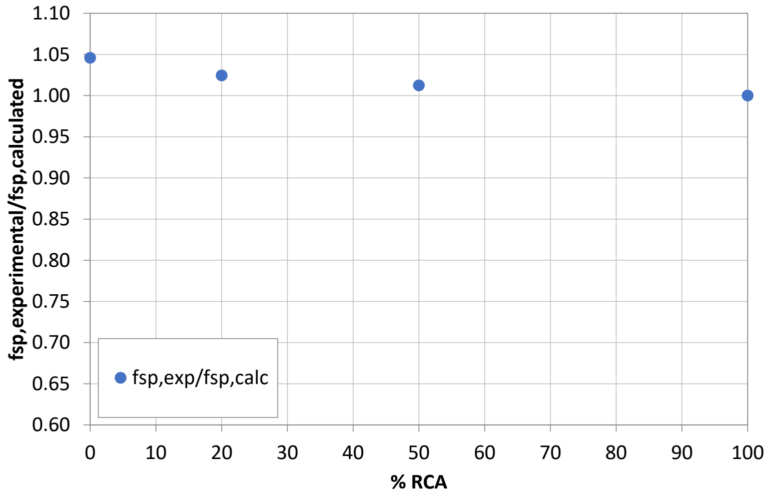


Figure IV-52. $f_{sp,experimental}/f_{sp,calculated\text{-}Eurocode}$ in SCRC mixes

Also in this case, the results have been presented along with those obtained with vibrated recycled concrete. Then, Figure IV-53 shows the ratios for different recycled percentages and for the "air-dry with extra-water-ADwEW" method obtained in section 2.5.2 with vibrated recycled concrete. Now, new points have been included in this figure. They represent the new ratios obtained with SCRC and SCC using the Eurocode expression. In this case, the ratios of conventional SCC are similar to those obtained with SCRC (Figure IV-53), and the relationship between SCRC vs SCC ratios and vibrated recycled concrete vs conventional concrete ratios is also similar.

This means that code expressions provide the same approximation degree in SCC and in SCRC when calculating the splitting tensile strength. Therefore, it is not necessary to modify them by introducing a correction coefficient. In this case, the use of experimental compressive strength to predict splitting tensile strength is sufficient for achieving the same approximation degree in SCRC as in SCC.

Once again in this case, the results also state that the incorporation of recycled concrete coarse aggregate affects SCC to a similar extent as it affects vibrated concrete with regards to splitting tensile strength.

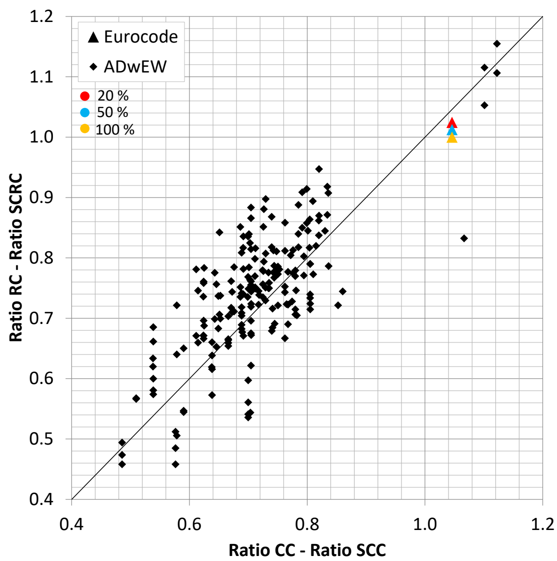


Figure IV-53. Ratio RC/SCRC vs Ratio CC/SCC (f_{sp})

3.5 Suitability of specific expressions

Lastly, the specific expressions adjusted with vibrated recycled concrete according to section 2.2.4 have been used to predict SCRC properties (modulus of elasticity and splitting tensile strength). The suitability of these specific expressions, adjusted with vibrated recycled concrete, was analysed, comparing their predictions with those obtained using the expressions proposed by the codes.

Firstly, code expressions (Eurocode) [EURO04] were used to calculate the modulus of elasticity and splitting tensile strength in the reference concrete, SCRC – 0%. Secondly, the final research proposals (Figure IV-36) presented in section 2.4.3 and 2.5.3 to predict the recycled concrete modulus and splitting tensile strength, respectively, were applied to SCRC mixes – 20%, 50% and 100%. These results are shown in Figure IV-54 and Figure IV-55.

In agreement with different authors [KHAY08, DOMO07], it can be seen that the code expression used in vibrated concrete overestimates the SCC modulus (Figure IV-54). In this regard, the specific expression adjusted with vibrated recycled concretes also overestimates the SCRC modulus. This result confirms that due to the lower coarse aggregate volume of SCC, its elastic modulus is going to be reduced and, therefore, when it is predicted using expressions adjusted with vibrated concretes, the prediction is going to overestimate the value in SCC and to a similar extent in SCRC. As can be seen in Figure IV-54, SCRC and SCC predicted values are in the lower area. This means that specific expressions are required to predict both the SCRC and SCC modulus.

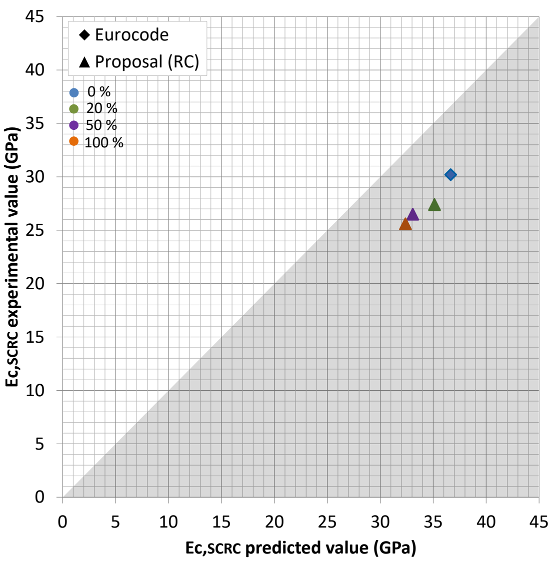


Figure IV-54. $E_{c,SCRC}$ experimental value vs $E_{c,SCRC}$ predicted value (RC proposal and codes)

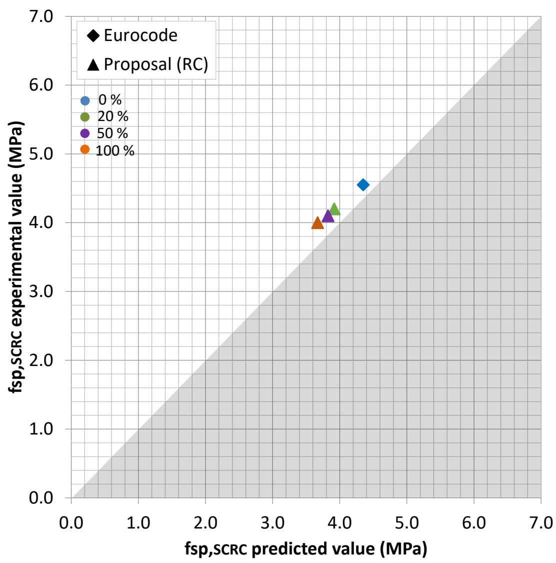


Figure IV-55. $f_{sp,SCRC}$ predicted value vs $f_{sp,SCRC}$ experimental value (RC proposal and codes)

On the other hand, also in agreement with different authors [KHAY08, DOMO07], it can be seen that the code expression, used in vibrated concrete, underestimates SCC tensile splitting strength (Figure IV-55). Following the same trend, the specific expression adjusted with vibrated recycled concretes also underestimates SCRC tensile splitting strength. This result confirms that due to the high content of ultra-fine materials, SCC splitting tensile strength is going to be increased and, therefore, when it is predicted using expressions adjusted with vibrated concrete, the prediction is going to underestimate the value in SCC and also to a similar extent in SCRC. As can be seen in Figure IV-55, SCRC and SCC predicted values are in the upper area. This means that specific expressions are required to predict SCRC splitting tensile strength as well as that of SCC.

In any case, accepting that code expressions (used in vibrated concrete) are suitable for the prediction of SCC modulus and splitting tensile strength, specific expressions adjusted with vibrated recycled concrete in this work can also be accepted to predict SCRC modulus and splitting tensile strength.

4 CONCLUSIONS

Firstly, this chapter has focused on the prediction of some of the most important properties of structural vibrated recycled concrete (compressive strength, modulus of elasticity and splitting tensile strength) taking into account, not only the recycled percentage and the quality of the recycled aggregates used, but also the production method. With the results obtained, the following main conclusions can be drawn:

- In general, compressive strength, modulus of elasticity and splitting tensile strength of recycled concretes decrease as the recycled concrete coarse aggregate percentage increases. Taking into account the production methods (to pre-soak the recycled aggregates (*pre-soaked-PS*), to work with air-dry aggregates increasing the amount of water (*air-dry with extra-water-ADwEW*), or to work with air-dry aggregates without any extra water (*air-dry without extra-water-AD*)), it has been concluded that *ADwEW* during mixing shows the best results. With this method the reductions in compressive strength, splitting tensile strength and modulus of elasticity are lower (especially when compared with the PS method) and, moreover, there is no need to increase the dosage of superplasticiser.
- Regarding the modulus of elasticity, it has been seen that its prediction code expression (according to Eurocode) has to be corrected to get the same approximation degree in recycled concretes as in conventional ones. In this regard, using multivariable regression, a correction coefficient has been adjusted providing good statistical indexes. This correction coefficient takes into account the recycled concrete compressive strength, production procedure, replacement ratio and recycled concrete coarse aggregate quality (considering it based on its water absorption). Different coefficients have been adjusted for each of the different mixing procedures.
- Regarding splitting tensile strength, it has been seen that its prediction code expression (according to Eurocode) does not need to be corrected to get the same approximation degree in recycled concretes as in conventional ones. The use of the compressive strength is enough to take into account the use of recycled aggregates.
- Lastly, specific expressions to predict the modulus of elasticity and the splitting tensile strength have been adjusted. For said purpose, the Eurocode expressions have been taken as a basis, modifying them to introduce the replacement ratio and the recycled concrete coarse aggregate quality (considering it, again, based on its water absorption). Also in this case, different expressions have been adjusted for each of the different mixing procedures considered, and the techniques used have been multivariable regression and genetic programming. In all cases, the expressions adjusted by means of genetic programming provide the best statistical indexes compared with the literature's proposals. Also, regarding the modulus of elasticity, the multivariable regression expressions improve the predictions proposed in the literature.

Secondly, the prediction proposals obtained with vibrated recycled concrete have been used to study the behaviour of self-compacting recycled concrete, and their accuracy was analysed during the use of this concrete. Regarding these results, the main conclusions are as follows:

- As in vibrated recycled concrete, SCRC compressive strength, modulus of elasticity and splitting tensile strength decrease when the content of recycled coarse aggregate increases. It has been confirmed that, regarding these properties, the incorporation of recycled concrete coarse aggregate affects SCC to a similar extent as vibrated concrete.

- It has been stated that code expression does not provide the same approximation degree in SCRC as in SCC when calculating modulus of elasticity. Consequently, it has been corroborated that it is necessary to modify this expression by introducing a correction coefficient. Therefore, the suitability of the correction coefficient, adjusted to maintain the same approximation degree in both conventional and recycled vibrated concrete modulus prediction, was analysed. The results aim to conclude that it can be used with the same accuracy in vibrated recycled concrete as in SCRC.
- Regarding splitting tensile strength, it has been stated that code expression provides the same approximation degree in SCRC as in SCC. Consequently, it has been corroborated that, as in vibrated recycled concrete, it is not necessary to modify this expression by introducing a correction coefficient.
- Finally, accepting that code expressions (used in vibrated concrete) are suitable for the prediction of SCC modulus and splitting tensile strength, specific expressions adjusted in this work with vibrated recycled concrete can also be accepted for predicting SCRC modulus and splitting tensile strength. In this case, it has to be expected that, as occurs in conventional SCC, modulus prediction is going to overestimate SCRC modulus and splitting tensile prediction is going to underestimate SCRC splitting tensile strength.

In conclusion, results state that the incorporation of recycled concrete coarse aggregate affects SCC to a similar extent as it affects vibrated concrete.

CHAPTER V
Results of self-compacting recycled concrete fresh behaviour: Rheology and Robustness

1 INTRODUCTION

As is well known, one of the main differences between conventional and recycled concrete (RC) is the high water absorption of recycled aggregate (especially due to adhered mortar) [SILV14, JUAN09, XIAO13b, AKBA13]. This aggregate property, as well as its moisture content when introduced into the mix, determine the effective water that influences the final properties of both fresh and hardened concrete. This fact makes exact proportions of RC difficult to control and, therefore, the design of specific mixing procedures is required [ETXE07b, FERR11, PELU09, SILV15a].

Furthermore, although the fresh and mechanical properties of self-compacting concrete (SCC) have been investigated by many researchers [KHAY08, OKAM03, KOVL11, DOMO07, HWAN06], there is a lack of knowledge on the production of SCC incorporating recycled concrete coarse aggregate. Thus, in recent years, some works [PAND13, PERE14, GRDI10, KOU09, TUYA14, YUAN12, FAKI12, FALE14, CORI11c, KEBA15] have been conducted aiming to clarify the potential use of this material and define the best way to incorporate it into SCC production.

SCC is renownedly more sensitive to small changes in raw material characteristics, mix parameters and mixing conditions than conventional vibrated concrete [KHAY08, NUNE13], i.e. it is less robust. Robustness is defined as the capacity of concrete to maintain its performance requirements (in a fresh or hardened state) when faced with some variations in component proportions, mixing procedures, transport or casting [KHAY08, NAJI11]. It should be noted that it also refers to the ability of a SCC mixture to maintain its filling ability, passing ability and segregation resistance during processing and placement [SHEN15]. The total quantity of mixing water is a key factor affecting the robustness of SCC [NAJI11]. Therefore, reducing or increasing the amount of water is expected to significantly influence its self-compactability. Other critical alterations can occur when there are changes in the content of cement, fly ash, superplasticiser, sand, gravel, etc. [GETT09].

In this context, the general objective of this research phase is to determine the effect of the incorporation of this specific type of aggregate on the fresh-state properties of self-compacting concrete over time. Therefore, this research focuses on studying the time-dependent rheological behaviour of self-compacting concrete including recycled concrete coarse aggregate and evaluating its robustness over time.

2 BACKGROUND AND OBJECTIVES

Traditionally, to control the high absorption of recycled aggregate, authors proposed two alternative mixing methodologies. In one of them, the aggregate is added dry or with its natural moisture and its absorption is compensated with the addition of an extra quantity of water, normally that required to take the recycled aggregate to 80% of its saturation state. In the second procedure, recycled aggregate is added to the mix after being immersed in water (pre-soaking method) for a pre-established time, usually 10 minutes. During this time, according to the literature, the recycled aggregate reaches 80% of saturation [SEAR14, CORI10a].

In parallel, the fundamental difference between vibrated concrete and self-compacting concrete is its fresh behaviour [BANF03]. Therefore, it is expected that a well-designed SCC provides similar mechanical properties to its equivalent vibrated concrete. Its fresh behaviour can be studied using empirical tests related to workability and rheological tests related to fluid behaviour.

Therefore, in hardened state, self-compacting recycled concrete (SCRC) is expected to present properties similar to those of its equivalent vibrated recycled concrete (as analysed in the previous chapter) and in fresh state, it is expected to show a greater influence of RC and SCC singularities (specific mixing procedures and a particular fresh behaviour, respectively).

Rheology has been defined as the study of the flow and deformation of materials [BARN00]. Regarding concrete, rheology is typically used to describe workability which is defined by the American Concrete Institute as the property that describes “the ease with which concrete can be mixed, placed, consolidated, and finished to a homogenous condition” [KOEH09].

In recent years, a great number of empirical tests allowing for the assessment of the three key fresh properties of self-compacting concrete (filling ability, passing ability and segregation resistance) have been developed [WALL11, LASK11, ROUS07, KHAY03]. Thus, in practice, a given SCC is empirically classified in terms of these properties: its filling ability is estimated mostly by its slump flow value, passing ability by its L-Box or J-Ring values and its stability, for example, by the sieve segregation test [ROUS08].

However, results of empirical tests cannot be compared directly and a single method does not exist to characterize all relevant aspects of the fresh-state of this type of concrete, as the use of different combinations of empirical tests are required to guarantee adequate workability [KOEH08].

In contrast, rheometry allows this phase of fresh-state characterization to be assessed through the measurements of rheological parameters in physical units. Since the 1970s, the study of rheology of fresh-state concrete has progressed significantly with the increasing use of rheometers. The objective of using rheology measurements is to provide scientific parameters that are comparable and capable of describing multiple aspects of workability, even when different devices are used. Three of the key concrete properties that can be measured in a single rheological test (static yield stress, dynamic yield stress and plastic viscosity) [BILL06] would lead to characterize concrete fresh behaviour as a fluid, thereby reducing the number of empirical tests.

The first objective of this research phase is to study the influence of the replacement percentage of natural coarse aggregate with recycled aggregate (from concrete waste) on the rheology and workability of self-compacting concretes over time. The second part focuses on the capacity of SCRC to maintain workability characteristics and rheological properties over time when variations are imposed on water (±W = ±3%), superplasticiser (±S = ±5%) and cement (±C = ±3%). In this chapter, the experimental results achieved while striving for both objectives are presented. These results will be analysed in the following chapters.

As was previously explained in Chapter III, a reference conventional SCC was designed with a water to cement (w/c) ratio of 0.46, SCRCs were designed using 20%, 50% and 100% of recycled coarse aggregate, and the following three mixing methods were used to produce concretes:

- M1 method: aggregates were used in dry-state conditions and an extra quantity of water was added during mixing. This was calculated to compensate the recycled aggregate absorption at 10 min (i.e. 80% of that at 24 h).
- M2 method: recycled aggregate was pre-soaked up to the 80% of its total water absorption capacity immediately before mixing.
- M3 method: recycled aggregate was used with 3% natural moisture and, again, an extra quantity of water was added during mixing according to the same criterion as in the M1 method.

Hence, ten types of concrete were obtained (SCRC0, SCRC20M1, SCRC50M1, SCRC100M1, SCRC20M2, SCRC50M2, SCRC100M2, SCRC20M3, SCRC50M3 and SCRC100M3) for their rheological properties to be studied.

The fresh behaviour of all mixes was studied using both empirical and rheological tests at 15, 45 and 90 min from cement-water contact, which was considered the reference time for performing all fresh concrete tests.

3 RHEOLOGY

3.1 Study of rheology with empirical tests

3.1.1 Empirical parameters. Limits

One of the key obstacles preventing faster and wider use of SCC is the absence of suitable testing methods to identify its three key fresh properties: filling ability, passing ability and resistance to segregation [TEST04] (workability characteristics).

Filling ability (also referred to as deformability or unconfined flowability) describes the ability of concrete to undergo change in shape and flow around obstacles, to completely encapsulate the reinforcement and fill the formwork under its own weight, without any mechanical consolidation [KHAY08].

Passing ability refers to the ability of concrete to pass among various obstacles and narrow spacing in the formwork without blockage, in the absence of any mechanical vibration.

Resistance to segregation (stability) describes the ability of concrete to maintain a homogeneous distribution of its various constituents. There are two types of stability characteristics in SCC technology: dynamic and static stability. Dynamic stability refers to the resistance of concrete to the separation of constituents during transport, placement, and spread into the formwork. Static stability refers to the resistance to segregation and bleeding after casting while the concrete is still in a plastic state [KHAY08].

It can be also described by its filling capacity, which is the ability of concrete to completely fill an intricate formwork or a formwork containing closely spaced obstacles, such as reinforcement. This is considered as the sum of the filling ability and passing ability.

Table V-1 shows the empirical test methods and the parameters measured to evaluate each workability characteristic. Individually, these tests study one or two of the three key properties, but none is capable of assessing them all and, as mentioned previously, there is no agreement as to which combination of tests is preferred.

Table V-1. Test methods and parameters measured to evaluate workability characteristics

Workability characteristic	Empirical test	Parameter
Filling ability	Slump flow	SF (flowability-filling ability) t500 (flowability-viscosity)
	V-funnel	tv (flowability-viscosity)
Passing ability	V-funnel	tv (narrow-opening passing ability)
	L-box	PL
	J-Ring	PJ t500J
Filling capacity (filling ability + passing ability)	J-Ring	SFJ
Resistance to segregation	Sieve segregation	SR

In order to analyse the influence of the recycled aggregate replacement in SCRC fresh behaviour (filling ability, passing ability, filling capacity and segregation resistance) using empirical tests, target limits were established for all empirical test parameters. These limits were established according to different standards, recommendations and studies. The reference SCC was designed to meet all of these requirements, hence, if the SCRC fulfilled the limits, it was considered a “suitable” self-compacting concrete.

Table V-2 summarises the target limits for empirical test parameters.

Table V-2. Target limits for empirical test parameters

Test	Parameter	Target limits	Reference
Slump flow	t500 (s)	[0.8-3.8]	European project called “Testing SCC” [TEST04]
	SF (mm)	[660-850]	European Standard EN 206-9 [EN206-9], SF2 and SF3 slump-flow classes
V-funnel	tv (s)	[5-25]	The lower limit according to “Testing SCC” project [TEST04] and the upper limit according to EN 206-9 [EN206-9]
L-box	PL	≥ 0.80	European Standard EN 206-9 [EN206-9]
J-Ring	t500J (s)	[2-5]	Relationship obtained in this research between t500 and t500J
	SFJ (mm)	[610-850]	Relation SF–SFJ > 50 mm of “Testing SCC” project [TEST04]. This difference represents a blocking assessment [CHAN10]: 0-25 mm no visible blocking, > 25 to 50 mm minimal to noticeable blocking, and > 50 mm noticeable to extreme blocking
	PJ (mm)	≤ 10	European Standard EN 206-9 [EN206-9]
Sieve segregation	SR (%)	≤ 20	European Standard EN 206-9 [EN206-9]

3.1.2 Empirical results

The following figures (Figure V-1 to Figure V-8) show the empirical test results achieved with SCRC obtained using methods M1 and M3. In some cases the result is not shown because the concrete was no longer a self-compacting concrete.

Regarding the slump flow test, the SF limits were satisfied by all SCRCs at an age of 15 min. The 100% replacement concrete did not reach the minimum limit at an age of 45 min, nor did the 50% replacement concrete at 90 min (Figure V-1).

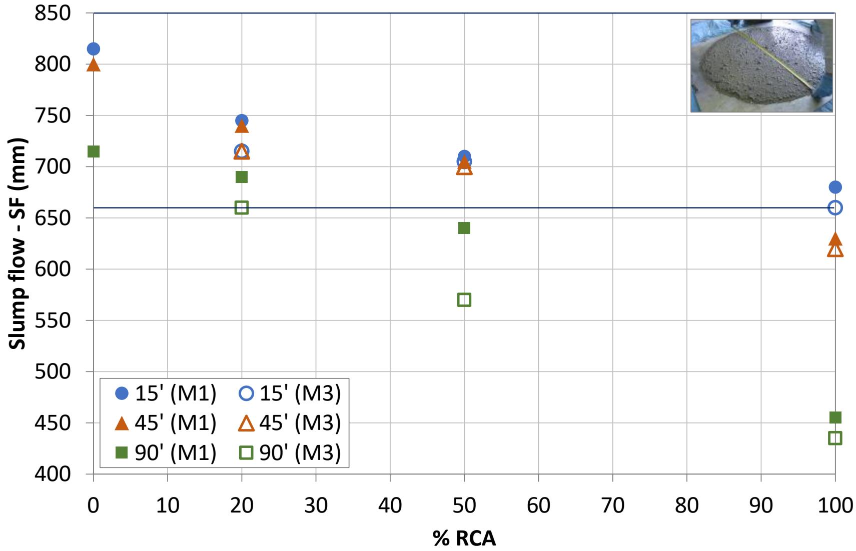


Figure V-1. Slump flow test – SF. M1 and M3 methods

In the case of the t500 parameter (Figure V-2), the limits were satisfied by SCRC with replacement percentages up to 50% and up to an age of 45 min. The mixes with 100% of RCA did not fulfil the limits at any age, although at 15 min the values were close to the upper limit. At an age of 90 min, only the reference mix and the 20% replacement concrete produced with the M1 method satisfied the acceptance range. In all cases, both parameters, SF and t500, increase as the RCA percentage increases and over time.

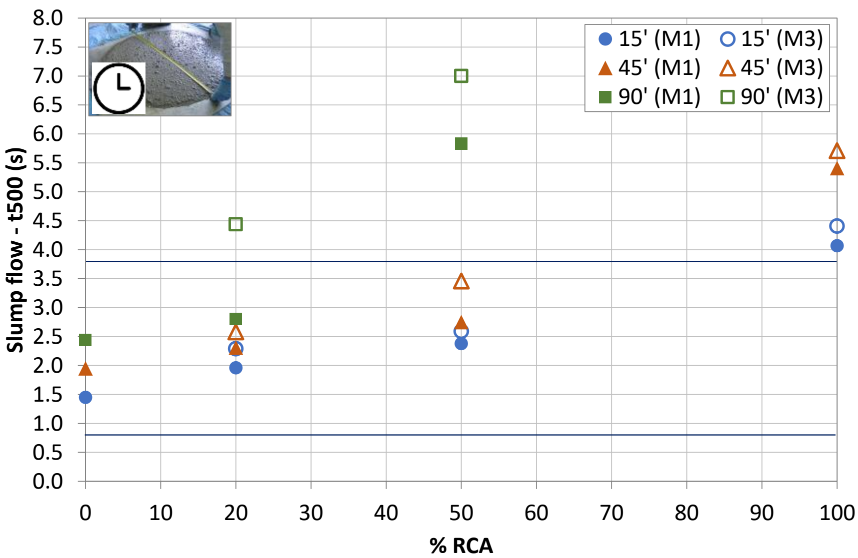


Figure V-2. Slump flow test – t500. M1 and M3 methods

The analysis of the V-funnel time shows that, up to an age of 45 min, only the reference concrete can be considered as showing “suitable” performance. The 20% SCRC produced with both methods and the 100% SCRC produced with the M3 method also satisfied the requirements, although only at an age of 15 min. All the other results did not fulfil the maximum limit time (Figure V-3).

Therefore, it can be seen that the tv results do not correlate well with the other empirical test results. Although it is said that V-funnel time estimates the apparent viscosity of a mixture, many factors play a role and influence this parameter: the amount, shape and size distribution of aggregates, the viscosity and amount of paste, the test operator, etc. Thus, many authors do not recommend this test for workability control [KHAY08, WÜST03].

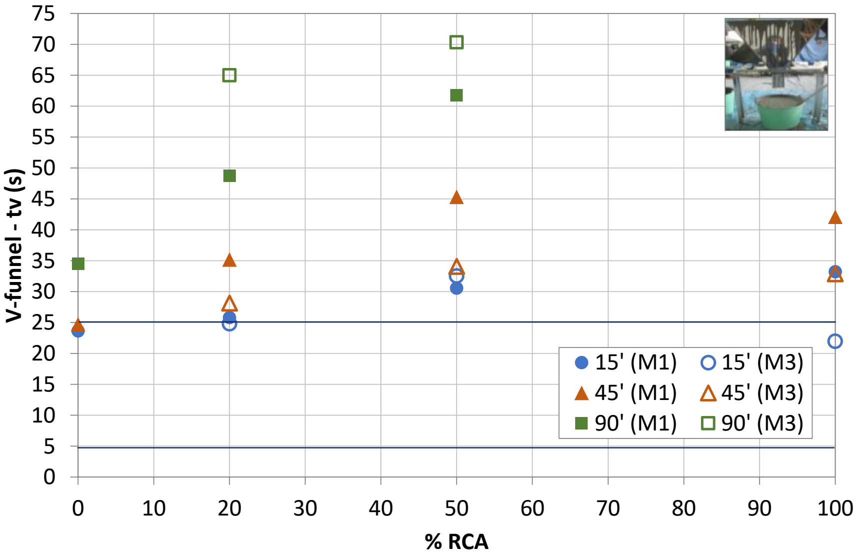


Figure V-3. V-funnel test – tv. M1 and M3 methods

The passing ability (PL, measured with the L-box test) limit was satisfied by all mixes at the minimum age of 15 and 45 min (Figure V-4), whereas at 90 min none of them reached the limit (nor did the reference mix).

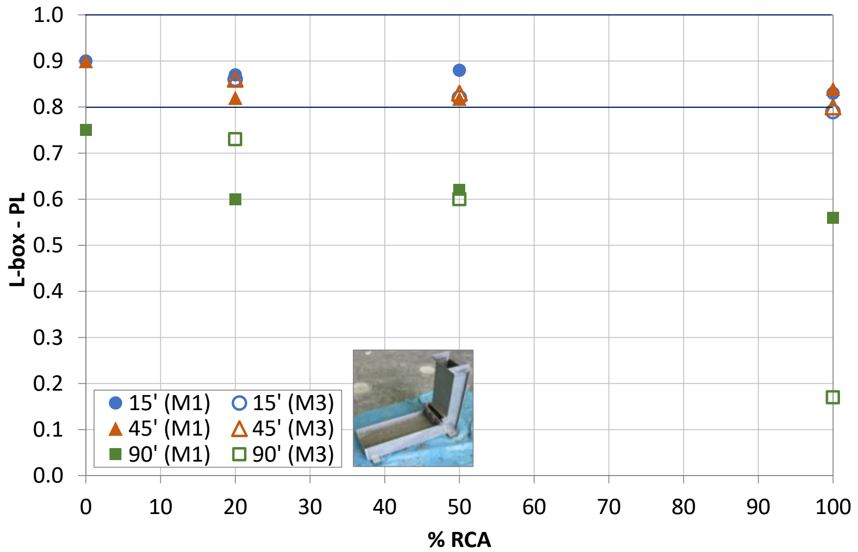


Figure V-4. L-box test – PL. M1 and M3 methods

In the J-Ring test (Figure V-5, Figure V-6 and Figure V-7), the highest stability over time took place with low recycled aggregate percentages (20%).

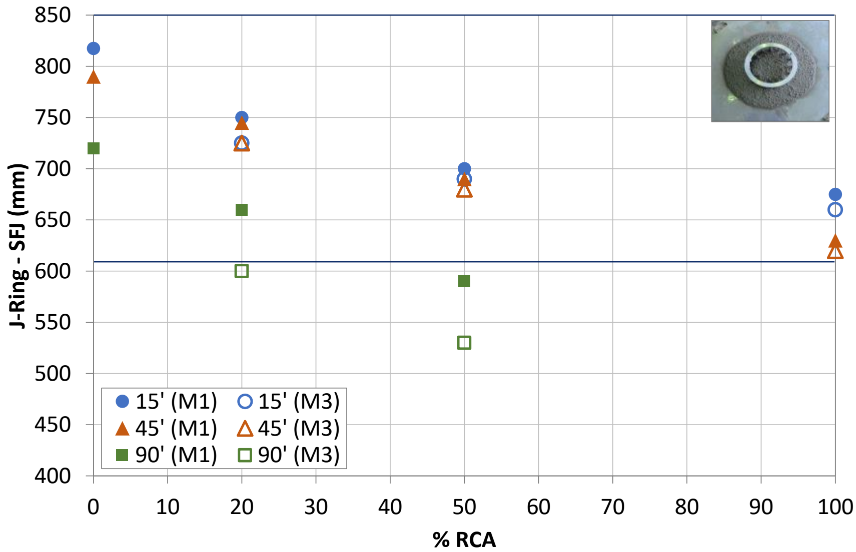


Figure V-5. J-Ring test – SFJ. M1 and M3 methods

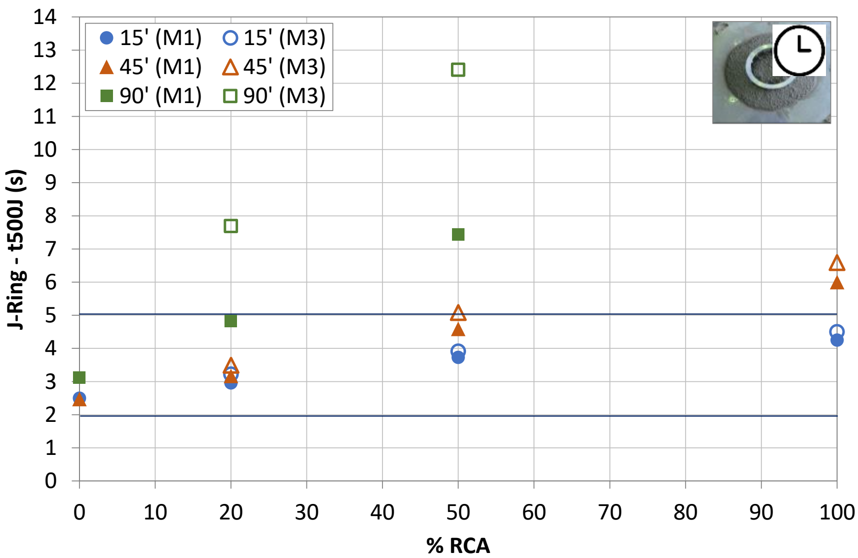


Figure V-6. J-Ring test – t500J. M1 and M3 methods

Again, at the age of 90 min, the mixes with substitution percentages of 50% and 100% presented the worst results. Moreover, the J-Ring blocking step (PJ) (Figure V-7) does not correlate well with the results of other empirical parameters [TEST04].

Finally, the limit value of 15% set for the sieve segregation test was satisfied by all mixes (Figure V-8). In this case, the recycled mixes showed a lower tendency to segregation than conventional SCC. The 100% replacement concretes showed values of around 5%. Although there is no lower limit, values under 5% can be considered excessive [EFNARC02].

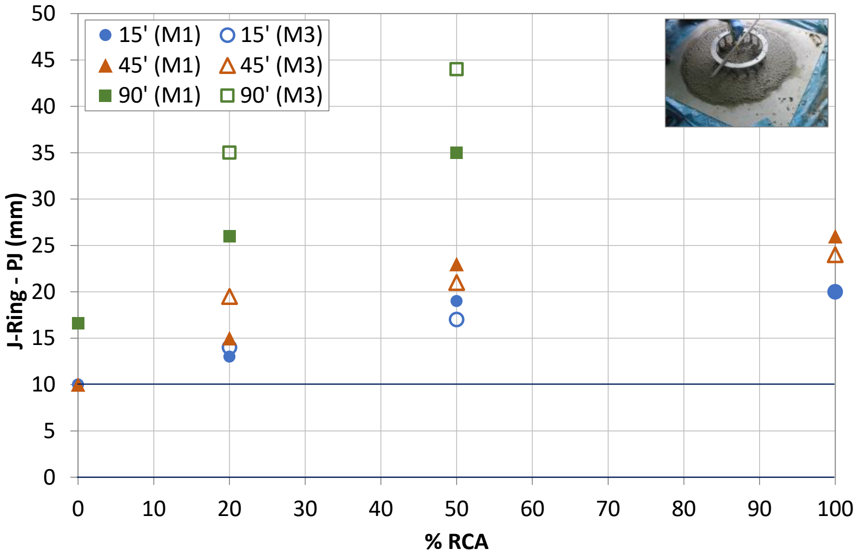


Figure V-7. J-Ring test – PJ. M1 and M3 methods

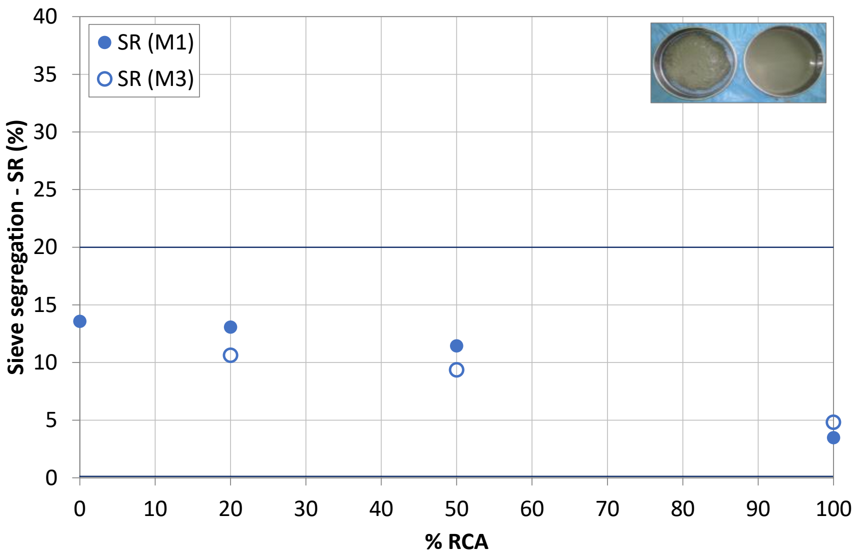


Figure V-8. Sieve segregation test – SR. M1 and M3 methods

The behaviour of concretes produced with the pre-soaking method (M2 method) displays noticeable differences from those obtained using the M1 and M3 methods, especially for mixes with replacement percentages of 50% and 100%.

Firstly, it has to be considered that this mixing method leads to an in increase in the effective water to cement ratio (Table III-8) of SCRC, significantly in 50% and 100% mixes. Then, as the effective water to cement ratio is different in the SCRC50M2 and SCRC100M2 mixes, they cannot be compared with the equivalent mixes of the M1 and M3 methods.

Secondly, with the M2 method, controlling the effective water to cement ratio is not easy, making it difficult to control the workability of SCC which is highly dependent on the free water content of the mix [TEST04]. The use of recycled coarse aggregates under pre-saturation conditions leads water to bleed from aggregate pores to cement paste [SEAR16], especially at early ages. This means that the real effective water to cement ratio of mixes with high replacement percentages, SCRC50M2 and SCRC100M2, is probably higher than that calculated in Table III-8 and therefore, there is more water available to “lubricate” the mix, which contributes to flowability.

Both of these issues lead the SCRC50M2 and SCRC100M2 mixes to present unique fresh behaviour. Therefore, it can be considered that, in general terms, the SCRC20M2 mix presents a flow behaviour similar to that of the SCRC20M1 and SCRC20M3 mixes. However, specific analysis focusing on the fresh behaviour of the SCRC50M2 and SCRC100M2 mixes has to be carried out.

Due to the high effective water to cement ratio, the flow properties of these two mixes show a convenient testing window between 15 and 45 min. In this window, their fresh behaviour remains constant or even improves before the self-compactability is reduced at 90 min (similar to the initial one at 15 min).

Regarding the slump flow test, both SF and t500 parameters (Figure V-9 and Figure V-10) show values related to higher flowability in the SCRC100M2 mix than in the SCRC50M2 mix, at all ages. This is due to the higher effective water to cement ratio in the 100% replacement concrete than in that of 50%. Both mixes showed the best results at 45 min, with similar results at the ages of 15 and 90 min.

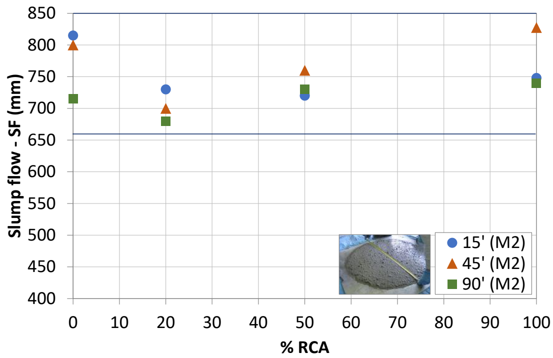


Figure V-9. Slump flow test – SF. M2 method

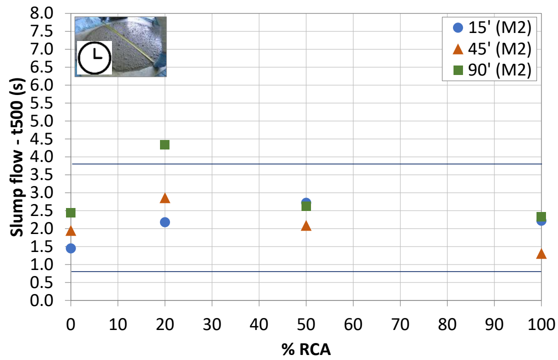


Figure V-10. Slump flow test – t500. M2 method

Concerning the V-funnel test, the SCRC50M2 did not fulfil the target limits at any age. However, the result at 45 min was the closest to the maximum time. The SCRC100M2 satisfied the tv limits at 15 and 45 min (Figure V-11). The PL parameter of the L-box test (Figure V-12) was in agreement with the target limits at 15 and 45 min for the SCRC50M2 mix. The SCRC100M2 mix did not fulfil them at 15 min, which may be a sign of segregation as it satisfied them at 45 and 90 min.

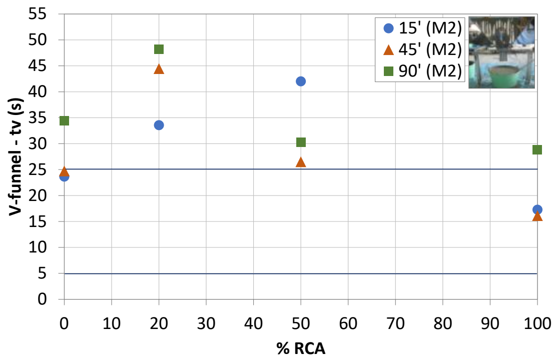


Figure V-11. V-funnel test – tv. M2 method

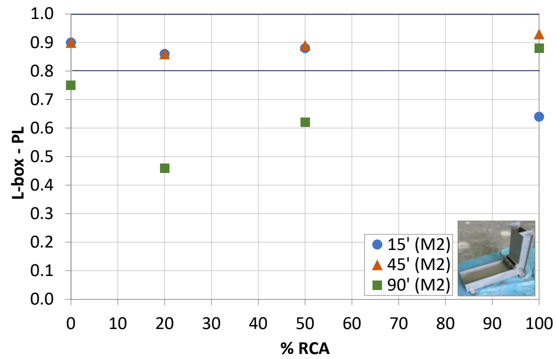


Figure V-12. L-Box test – PL. M2 method

Regarding the J-Ring test, the same comments can be made for both the SFJ and t500J parameters (Figure V-13 and Figure V-14). The SCRC50M2 mix keeps its self-compacting condition over time, although the best results were again at 45 min. At 15 min, the SCRC100M2 mix showed an SFJ above the maximum limit and a t500J below the minimum limit. As in the L-box test, this fact is surely related to segregation. This concrete at 45 and 90 min fulfilled the target limits and also the best results were at an age of 45 min.

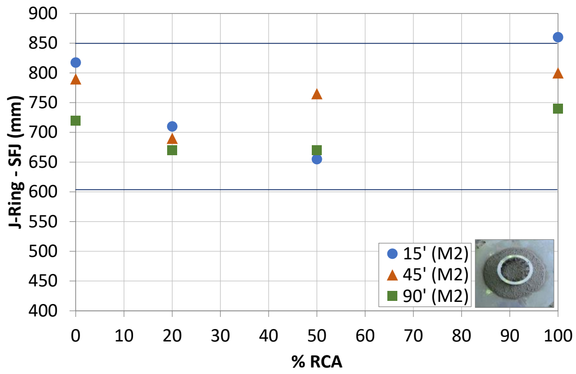


Figure V-13. J-Ring test – SFJ. M2 method

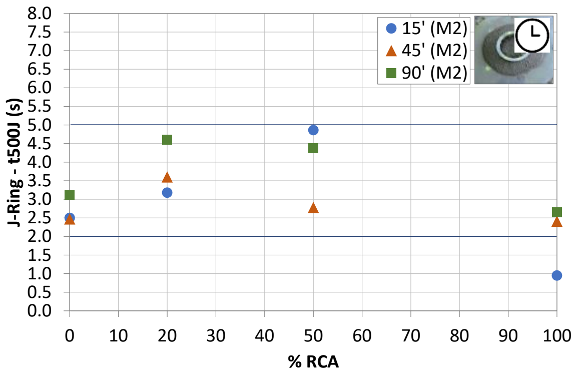


Figure V-14. J-Ring test – t500J. M2 method

Regarding the PJ parameter (Figure V-15), the behaviour does not correlate well with other empirical tests as occurred in the M1 and M3 methods. The SCRC50M2 did not fulfil the maximum blocking step required at any age, although the value at 45 min was quite close to the limit. SCRC100M2 satisfied that limit in the short term but not at 45 and 90 min, with the results at these times being quite similar.

Lastly, with regards to the sieve segregation test (Figure V-16), both mixes, SCRC50M2 and SCRC100M2, exceeded the maximum limit. In the case of the SCRC50M2 mix, the value was under 30%, and therefore, it could be accepted as long as tests on site (required in this case [EFNARC02]) provide suitable performance. However, the SCRC100M2 mix showed a value over 30%, which is considered as a strong likelihood of segregation.

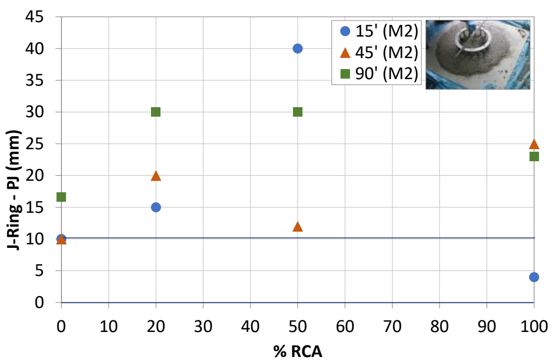


Figure V-15. J-Ring test – PJ. M2 method

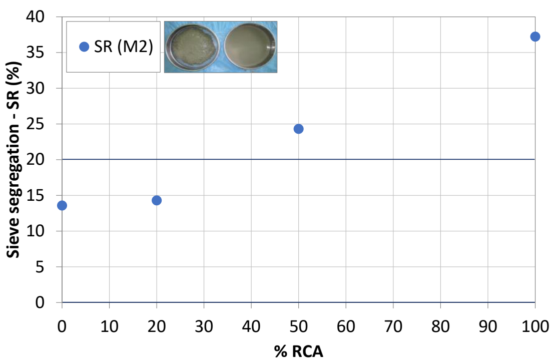


Figure V-16. Segregation test – SR. M2 method

In conclusion, although concretes made using the M2 method tend to satisfy the target limits, their tendency towards segregation is evident when high replacement percentages are used. Moreover, from an industrial point of view, this method is unfeasible due to the requirement of a pre-soaking time which is too long, especially when high quantities of recycled aggregate are needed. Finally, this method makes it very difficult to control the effective water to cement ratio, thereby hindering the control of workability in SCC. Therefore, pre-soaking would not be recommended for producing SCRC with replacement percentages above 20%.

3.2 Study of rheology with rheological tests

3.2.1 Rheological parameters. Rheological models

As aforementioned, rheology allows the characterization of fresh-state concrete to be assessed by measuring rheological parameters in physical units. Therefore, the fresh-state behaviour of SCRC was also measured using a rotational rheometer and the results obtained are shown in this sub-section. Table V-3 summarises the rheological tests and the parameters measured.

Table V-3. Rheological tests and parameters measured

Rheological test	Parameter
Stress growth test	Static yield stress (Pa)
Flow curve test	Plastic viscosity (Pa·s)
	Dynamic yield stress (Pa)

SCC can be classified as a thixotropic liquid having a yield stress, showing shear thickening and having a decrease in workability (fluidity) over time due to chemical reactions [FEYS07]. In literature, it is shown that the choice of rheological model influences the estimated value of the yield stress. In case of shear-thickening, the well-known Bingham model (Eq. 1) always delivers the lowest estimation (sometimes even physically impossible values). Although the vast majority of cement-based materials can be considered as Bingham materials [FEYS13], the Bingham model cannot be always applied to describe the rheological properties of SCC, due to the generation of negative yield stresses.

$$\tau = \tau_1 + \mu_p \dot{\gamma} \tag{1}$$

Where:

τ is the shear stress (Pa)

τ_1 is the yield stress (Pa)

μ_p is the plastic viscosity of Bingham model (Pa·s)

$\dot{\gamma}$ is the shear rate (1/s)

By means of the application of the so-called Herschel-Bulkley approach negative yield stresses can be avoided [WÜST05] (Eq. 2).

$$\tau = \tau_1 + k\dot{\gamma}^n \tag{2}$$

Where:

τ is the shear stress (Pa)

τ_1 is the yield stress (Pa)

k is the consistency factor of Herschel-Bulkley model (Pa·s^n)

$\dot{\gamma}$ is the shear rate (1/s)

n is the consistency index of Herschel-Bulkley model (power)

The Herschel-Bulkley model describes the behaviour better, but it has a parameter with a variable dimension and it overestimates the yield stress, due to a mathematical restriction in the region of low shear rates [FEYS07]. However, from a practical viewpoint, a model with three curve parameters may be difficult to handle (especially if the aim is to specify the rheological characteristics and control them by optimizing the mixture-design) [LARR98].

In fact, in this 3-parameter model, only the yield stress can physically be interpreted [WÜST05]. So, a combined method has been developed and, in this, the Herschel-Bulkley approach is combined with the Bingham approach. This is the modified Bingham model (Eq. 3).

$$\tau = \tau_1 + \mu\dot{\gamma} + c\dot{\gamma}^2 \quad (3)$$

Where:

τ is the shear stress (Pa)

τ_1 is the yield stress (Pa)

μ is the linear term of modified Bigham model (Pa·s)

$\dot{\gamma}$ is the shear rate (1/s)

c is the second order term of modified Bigham model (Pa·s^2)

Then, the modified Bingham model, being an extension of the Bingham model and a second order Taylor development of the Herschel-Bulkley model, is suitable to model the rheology of SCC. It is a worthy alternative for Herschel-Bulkley since it accurately describes shear-thinning and moderate shear-thickening behaviour, and does not induce a mathematical restriction on the zero-shear viscosity [FEYS13].

However, it is recommended to keep the applied rheological model simple, i.e. the Bingham model, describing yield stress and plastic viscosity. If non-linearity is indeed observed, and is not the result of a measurement error, the modified Bingham model is recommended instead of Herschel-Bulkley model, as the yield stress estimation appears to be more reliable [WALL15].

On the other hand, some measurements can result in apparent non-linear behaviour, due to thixotropy and segregation, and then they should be eliminated [WALL15]. The effect of thixotropy should be verified by checking the equilibrium of the torque at each rotational velocity step on the flow curve measurement. Segregation should be examined visually both during and after the test.

Thus, the stepwise decrease of rotational speed was analysed in the flow curve tests carried out. Each step equilibrium was verified by plotting torque versus time and assuring that, on average, the torque was constant for the duration of testing. If torque shows a decreasing trend at a given rotational speed, the data point should be eliminated to avoid an erroneous conclusion of shear-thickening.

Finally, in this research the two points related to the first two steps (the two highest rotational speeds) were not considered and both were eliminated from the data set. Then, keeping in mind all the above, the Bingham model was applied to the five data points with the lowest rotational velocities (Figure V-17, Figure V-18, Figure V-19, Figure V-20, Figure V-21, Figure V-22, Figure V-23, Figure V-24, Figure V-25 and Figure V-26).

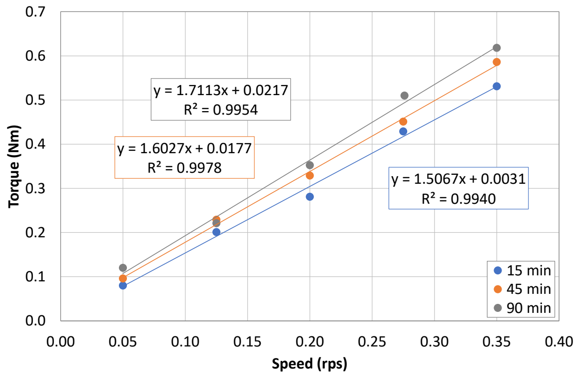


Figure V-17. Flow curves of the SCRC0 mix

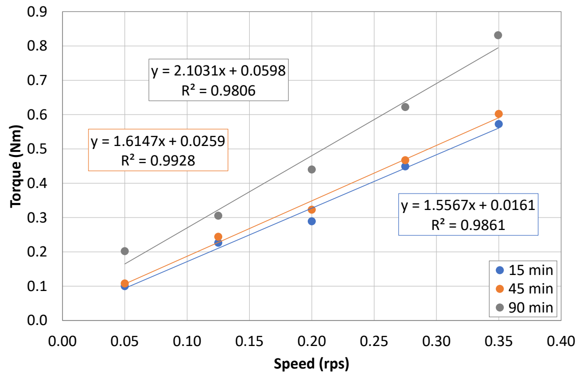


Figure V-18. Flow curves of the SCRC20M1 mix

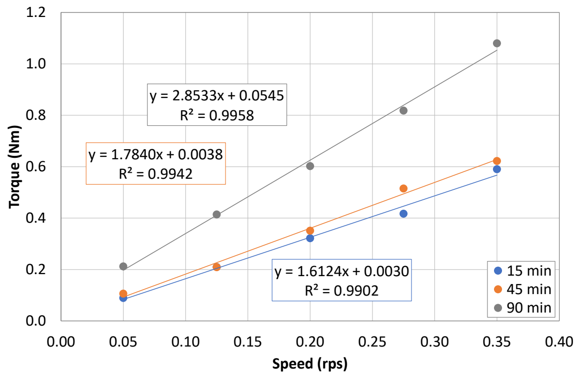


Figure V-19. Flow curves of the SCRC50M1 mix

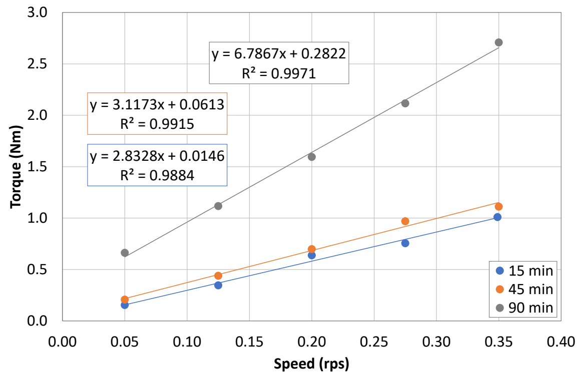


Figure V-20. Flow curves of the SCRC100M1 mix

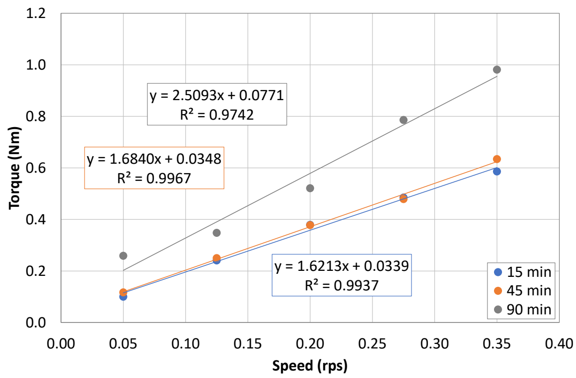


Figure V-21. Flow curves of the SCRC20M2 mix

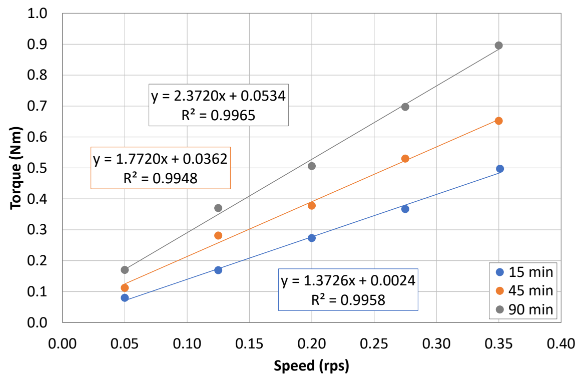


Figure V-22. Flow curves of the SCRC50M2 mix

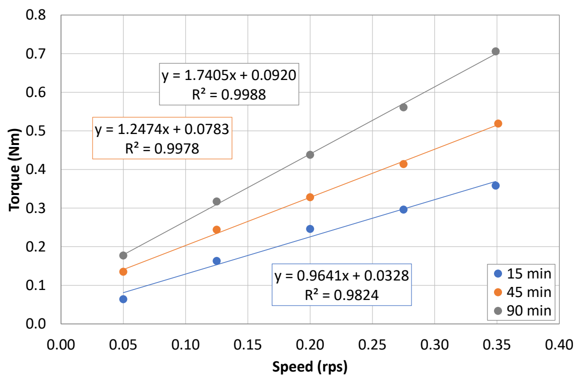


Figure V-23. Flow curves of the SCRC100M2 mix

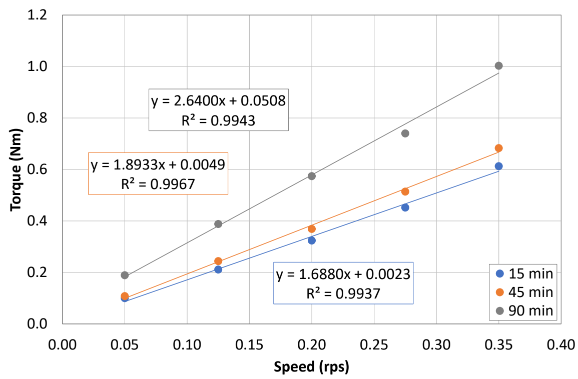


Figure V-24. Flow curves of the SCRC20M3 mix

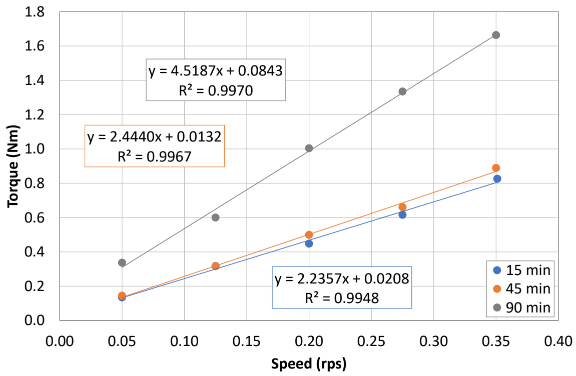


Figure V-25. Flow curves of the SCRC50M3 mix

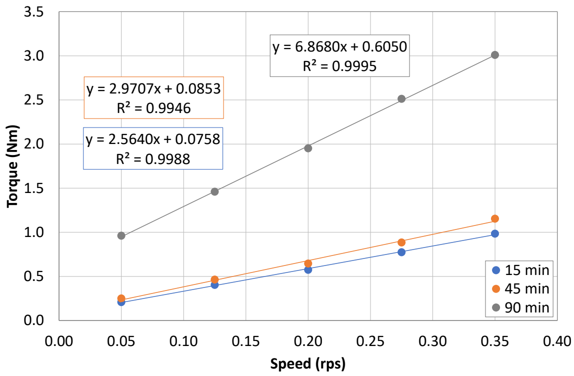


Figure V-26. Flow curves of the SCRC100M3 mix

Furthermore, the calculation of fundamental units must take into account the fact that some of the concrete in the rheometer may not flow (the effect of plug flow). It has been proven, in rheometers with similar dimensions to the one used in this research, that neglecting the plug flow induces only small errors, which are of the same order of magnitude as the measurement precision [FEYS13].

Consequently, the Reiner-Riwlin equations (Eq. 4-5) for the Bingham 5-lowest model were applied to the experimental data. This procedure transforms a relationship between torque and rotational (or angular) velocity into a relationship between shear stress and shear rate. It does not provide a point-to-point transformation, but it expresses the obtained relationship in fundamental units (Pa and Pa s).

$$\tau_1 = \frac{\left(\frac{1}{R_1^2}-\frac{1}{R_2^2}\right)}{4\pi h ln\left(\frac{R_1}{R_2}\right)} G \tag{4}$$

$$\mu_p = \frac{\left(\frac{1}{R_1^2}-\frac{1}{R_2^2}\right)}{4\pi^2 h} H \tag{5}$$

Where:

R_1 is the vane radius (m)

R_2 is the outer container radius (m)

h is the vane height (m)

G is the intersection of curve in T-N graph with T-axis (Nm)

H is the slope of straight line in T-N graph (Nm·s)

Thus, the flow curve test results were analysed both in relative and fundamental units (Table V-4). To compute relative units, a straight line is fit to the torque versus rotation speed data. The intersection with the “Y” axis is denoted as G (Nm) and the slope is denoted as H (Nm·s). The G and H values are related to dynamic yield stress and plastic viscosity respectively. To turn the relative units into fundamental units, dynamic yield stress (Pa) and plastic viscosity (Pa·s), the Bingham model was considered.

Table V-4. Flow curve test results

Relative units: T = G + HN	Fundamental units: $\tau = \tau_1 + \mu_p \dot{\gamma}$
T = torque (Nm)	τ = shear stress (Pa)
Y = "Y-value" (Nm), related to τ_0	τ_1 = yield stress (Pa)
V = "V-value" (Nm·s), related to μ_p	μ_p = plastic viscosity (Pa·s)
N = rotation speed (rps)	$\dot{\gamma}$ = shear rate (1/s)

3.2.2 Rheological results

Figure V-27 shows the static yield stress of conventional SCC and SCRC as a function of recycled coarse aggregate (RCA) percentage and of the time elapsed (15, 45 and 90 min) since the cement-water contact. Figure V-28 and Figure V-29 show the same relationship in the case of plastic viscosity and dynamic yield stress respectively.

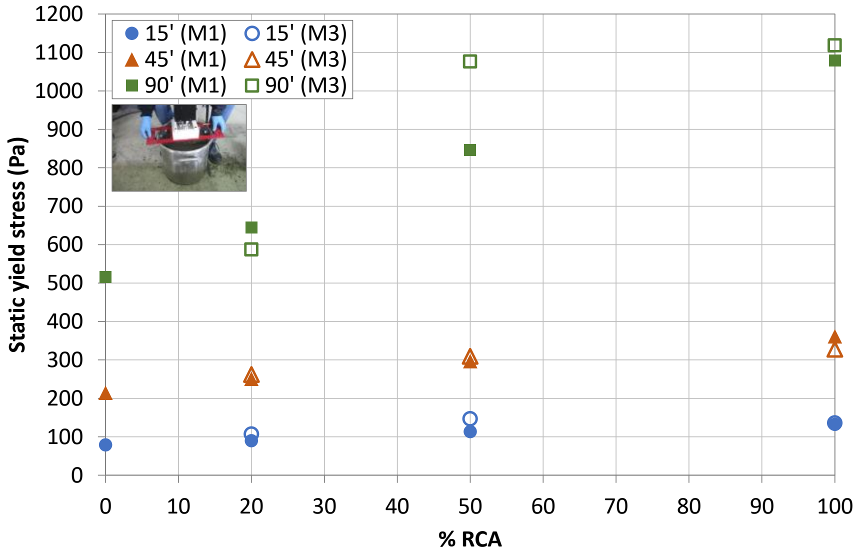


Figure V-27. Static yield stress. M1 and M3 methods

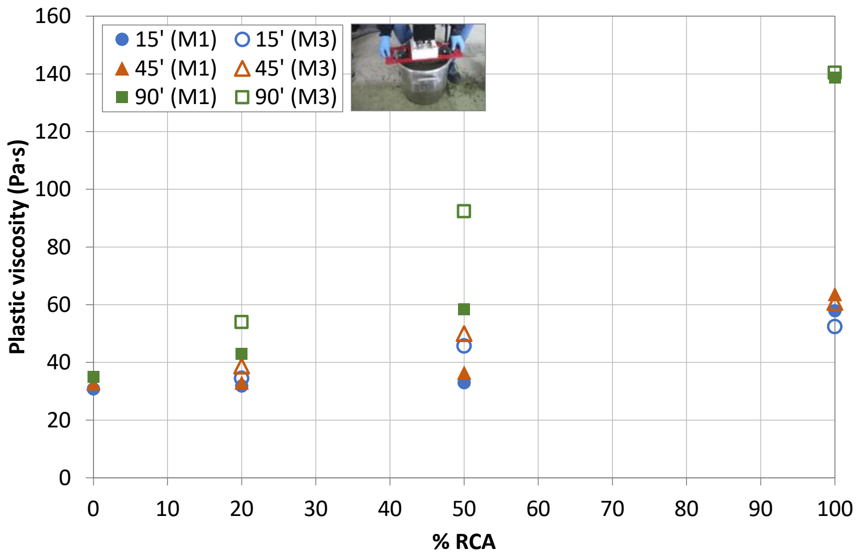


Figure V-28. Plastic viscosity. M1 and M3 methods

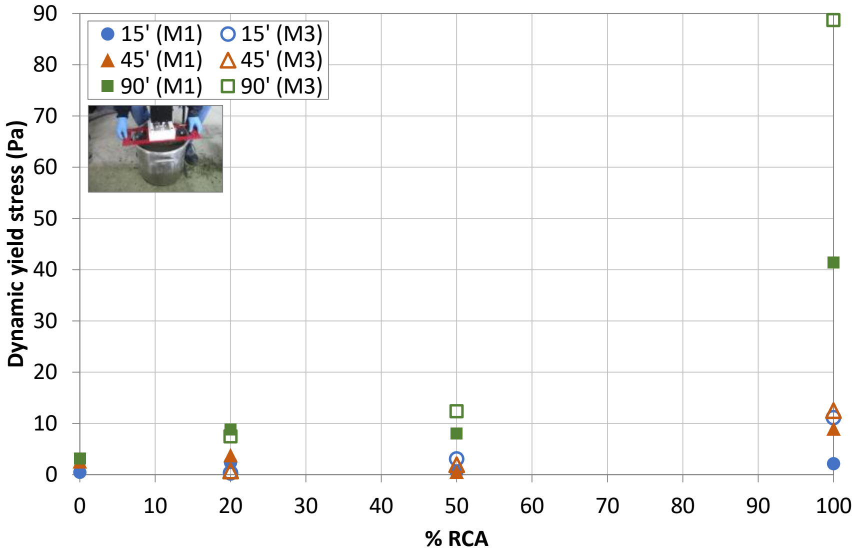


Figure V-29. Dynamic yield stress. M1 and M3 methods

It is demonstrated that SCRC, up to 20% of replacement, shows a rheological performance that satisfies the standard thresholds of self-compacting behaviour and these values are similar to reference SCC values (Figure V-27 and Figure V-28). Hence, the production of recycled concrete by adding extra water to compensate the high water absorption of recycled aggregate and using recycled concrete coarse aggregate up to 20% (substitution in volume) guarantees the self-compacting behaviour of this concrete (even up to a mix age of 90 min).

The analysis of the time-dependent evolution of static yield stress and plastic viscosity leads to the conclusion that RCA incorporation (20%, 50% and 100%) does not involve significant changes (comparing with 0%) until 45 min (Figure V-27 and Figure V-28). However, from 45 min to 90 min, the values are different from those obtained in 0% SCRC, especially in 100% SCRC.

As in the analysis of empirical tests, the results using the M2 method and with replacement percentages of 50% and 100% cannot be compared to those obtained with the other methods.

In general terms, in these mixes, the static yield stress increases significantly over time, whereas the plastic viscosity is lower than that of mixes produced with the M1 and M3 methods (Figure V-30 and Figure V-31). The dynamic yield stress also increases over time (Figure V-32) but to a lesser extent.

The SCRC20M2 mix presents a rheological behaviour similar to that of the SCRC20M1 and SCRC20M3 mixes when all rheological parameters are analysed (static yield stress, plastic viscosity and dynamic yield stress).

However, again, mixes with high replacement percentages (50% and 100%) present a specific behaviour. Regarding the static yield stress (Figure V-30), both the SCRC50M2 and SCRC100M2 mixes showed a similar behaviour to the corresponding mixes of the M1 and M3 methods at an age of 15 min. However, the values at 45 and 90 min were considerably higher than those obtained with the other methods, due to the greater segregation tendency of these mixes. The effect of segregation is clear when concretes are tested after being at rest, as occurs when measuring static yield stress. Unlike the empirical tests procedure, concrete is not remixed before the stress growth test. It is well known that if concrete is remixed (empirical tests), the effect of segregation is mitigated.

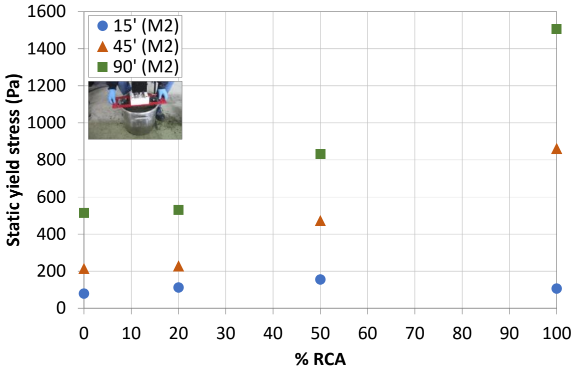


Figure V-30. Static yield stress. M2 method

Regarding plastic viscosity (Figure V-31), the SCRC50M2 mix showed results quite similar to those of the homologous mixes produced with the M1 and M3 methods, although with slightly lower values. The results of the SCRC100M2 mix were lower than those obtained with the others two methods.

Finally, concerning the dynamic yield stress (Figure V-32), again the SCRC50M2 mix showed values comparable with those of the mixes produced with the M1 and M3 methods. The SCRC100M2 showed values lower than the corresponding mixes of the other two methods, with the greatest difference shown in the result at an age of 90 min.

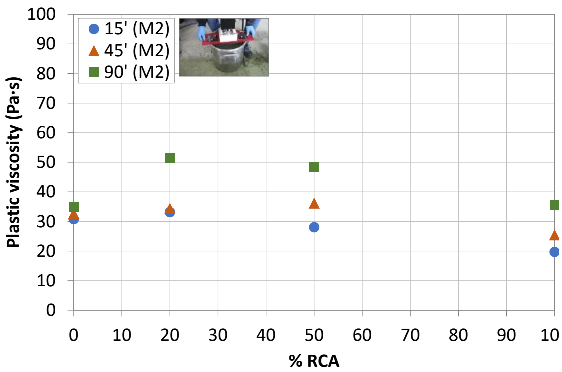


Figure V-31. Plastic viscosity. M2 method

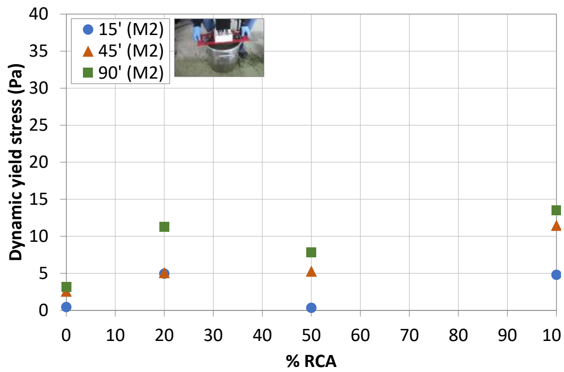


Figure V-32. Dynamic yield stress. M2 method

To finish this sub-section, Table V-5 shows the numerical results of rheological parameters obtained with the Bingham model on the five lowest points and additionally, the dynamic yield stress was calculated from the slump flow measurements, by means of Eq. 5 [ROUS05]:

$$\tau_1 = \frac{225 \cdot \rho \cdot g \cdot V^2}{128 \cdot \pi^2 \cdot R^5} \qquad (5)$$

Where:

ρ is the material density

V is the test sample volume

R is the radius of slump flow

This semiempirical equation is valid up to a yield stress of around 210 Pa, which corresponds to a minimum slump flow of 450 mm, if the standard Abram's cone is used in its original way (not inverted) [FEYS13]. The yield stress values obtained with rheological models (Bingham, Herschel-

Bulkley and modified Bingham) can be compared to the yield stress value calculated from slump flow measurements.

Table V-5. Rheological parameters (rheological model and slump flow results)

Mix	Age (min)	Bingham 5-lowest		Slump flow	
		τ_1 (Pa)	μ_p (Pa·s)	SF (mm)	τ_1 (Pa)
SCRC0	15	0.45	30.80	815	11.35
	45	2.60	32.77	800	12.45
	90	3.18	34.99	715	21.84
SCRC20M1	15	2.36	31.82	745	17.66
	45	3.80	33.01	740	18.26
	90	8.77	43.00	690	25.91
SCRC20M2	15	4.97	33.15	730	19.44
	45	5.10	34.43	700	23.98
	90	11.30	51.30	680	27.72
SCRC20M3	15	0.34	34.51	715	21.77
	45	0.72	38.71	715	21.77
	90	7.45	53.97	660	32.49
SCRC50M1	15	0.44	32.96	710	22.37
	45	0.56	36.47	705	23.17
	90	7.99	58.33	640	37.58
SCRC50M2	15	0.35	28.06	720	20.84
	45	5.31	36.23	760	15.90
	90	7.83	48.49	730	19.45
SCRC50M3	15	3.05	45.71	705	23.29
	45	1.94	49.96	700	24.14
	90	12.36	92.38	570	67.43
SCRC100M1	15	2.14	57.91	680	27.31
	45	8.99	63.73	630	40.01
	90	41.37	138.75	455	203.62
SCRC100M2	15	4.81	19.71	750	16.62
	45	11.48	25.50	830	10.03
	90	13.49	35.58	740	17.54
SCRC100M3	15	11.11	52.42	660	31.34
	45	12.51	60.73	620	42.84
	90	88.70	140.41	435	251.97

Ideally, the ratio of the yield stress obtained with the rheometer relative to the yield stress calculated from the slump flow measurement should be equal to 1. The yield stress of concrete measured by slump flow is not 100% accurate. The measurements depend on the operator, the material used for the base plate, the moisture of the plate, etc. The results are even influenced by the coarse aggregates of the concrete as they have a dimension of the same order of magnitude as the thickness of the flowing material. This validity range is unfortunately the range in which the sample height is closed to the size of the gravel, which strongly reduces the meaningfulness of the measured slump [ROUS05].

Due to inaccuracies in measuring the yield stress in the rheometer and in estimating the yield stress by means of slump flow, the ideal 1-to-1 relationship was not obtained for the imposed rheological model, the Bingham 5-lowest (Table V-5). This fact has been also detected by other authors using that and other rheological models [FEYS13].

4 ROBUSTNESS

In the “Robustness” phase, the same mixes studied in the “Rheological” phase (named as “base” mixes) were modified varying the water (±W = ±3%), superplasticiser (±S = ±5%) and cement (±C = ±3%) content. Therefore, in this section, results will be shown focusing on the behaviour of mixes obtained with these variations.

Rheology and workability over time (15, 45 and 90 min) of all the new mixes were measured. When water and superplasticiser variations were imposed, the M1 and M3 methods were used, and the new mixes were analysed using all the empirical and rheological tests. When cement variations were made, only the M1 method was used and the new mixes were studied throughout all the rheological tests and also, the following empirical tests: slump flow, V-funnel (this only at 15 min), J-Ring and sieve segregation.

4.1 Study of robustness with empirical tests

In this “Robustness” phase, the target limits concerning the empirical parameters used to define the self-compacting behaviour were the same as in the “Rheology” phase.

Regarding the slump flow test (Table V-6, Figure V-33, Figure V-37 and Figure V-41), the target limits for the SF parameter were satisfied by the reference SCC (SCRC0) at all ages and for all variations.

The 20% replacement concretes (SCRC20M1 and SCRC20M3) satisfied the limits at 15 and 45 min, but not at 90 min when the water or superplasticiser decreases, for both the M1 and M3 methods. In the case of cement variations, the limits were not satisfied at an age of 90 min when the cement increases.

The 50% replacement concretes (SCRC50M1 and SCRC50M3) showed differences according to the working method. With the M1 method, regardless of the variation introduced, the target limits were satisfied at 15 and 45 min. At an age of 90 min, only when the water increases or the cement decreases, the behaviour was kept self-compacting, according to the established limits. With the M3 method, at 15 and 45 min the SCRC50M3 did not satisfy the limits when the water decreases. At 90 min, this mix stopped being self-compacting in all cases.

Concerning the 100% replacement concretes, SCRC100M3 fulfils the target limits at 15 min only with the baseline mix. However, SCRC100M1 only stops being self-compacting when the water or superplasticiser decreases. This condition is also lost when the cement increases at an age of 45 min (as it already occurred with its base mix). At an age of 90 min, and for any variation, it does not fulfil the minimum limit established for the SF parameter.

These results point out the differences between the M1 and M3 methods when the robustness of mixes with high replacement percentages is analysed. The correct calculation of the aggregates moisture is known to be important in conventional SCC [TEST04] and it can be seen that it is even more important when recycled aggregates are used. At this stage, it can be said that the moisture condition of the aggregates seems to have a significant effect on SCRC fresh-state behaviour and its change over time.

When the t500 parameter is analysed, it can be seen that the target limits were not satisfied by the reference SCC (SCRC0) at an age of 90 min when the water decreases. Regarding the SF parameter, the SCRC20M1 mix did not fulfil the limits established for the t500 time at 90 min when the water or superplasticiser decreases or the cement increases. Also, regarding the SF parameter, the SCRC50M1 mix satisfied the t500 limits at ages of 15 and 45 min, although at 90 min again it only fulfilled them when the water increases or cement decreases.

With regards to the M3 method, the SCRC20M3 mix did not satisfy the t500 target limits at an age of 90 min when the water or superplasticiser decreases (and neither did the base mix). With regards to the SF parameter, the SCRC50M3 mix did not satisfy the maximum time at 15 and 45 min when the water decreases or any variation at 90 min. Finally, the SCRC100M3 mix only fulfilled the t500 requirements at 15 and 45 min when the water increases.

Table V-6. Slump flow test requirements

Mix	Age	SF - [660-850] mm							t500 - [0.8-3.8] s						
	(min)	Base	W+	W-	S+	S-	C+	C-	Base	W+	W-	S+	S-	C+	C-
SCRC0	15	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	45	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	90	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y
SCRC20M1	15	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	45	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	90	Y	Y	N	Y	N	N	Y	Y	Y	N	Y	N	N	Y
SCRC50M1	15	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	45	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	90	N	Y	N	N	N	N	Y	N	Y	N	N	N	N	Y
SCRC100M1	15	Y	Y	N	Y	N	Y	Y	N	Y	N	Y	N	N	Y
	45	N	Y	N	Y	N	N	Y	N	Y	N	Y	N	N	Y
	90	N	N	N	N	N	N	N	N	N	N	N	N	N	N
SCRC20M3	15	Y	Y	Y	Y	Y			Y	Y	Y	Y	Y		
	45	Y	Y	Y	Y	Y			Y	Y	Y	Y	Y		
	90	Y	Y	N	Y	N			N	Y	N	Y	N		
SCRC50M3	15	Y	Y	N	Y	Y			Y	Y	N	Y	Y		
	45	Y	Y	N	Y	Y			Y	Y	N	Y	Y		
	90	N	N	N	N	N			N	N	N	N	N		
SCRC100M3	15	Y	N	N	N	N			N	Y	N	N	N		
	45	N	N	N	N	N			N	Y	N	N	N		
	90	N	N	N	N	N			N	N	N	N	N		

Note: Y: Yes, it meets the limits; N: no, it does not meet the limits

Regarding the V-funnel test (Table V-7, Figure V-34, Figure V-38 and Figure V-41), the reference SCC satisfied the target limits for tv time at an age of 15 min when the water or superplasticiser increases and for both cement variations (increase or decrease). At 45 min, the behaviour was the same (for cement variations this test was only made at 15 min). At 90 min, this concrete did not fulfil the limits in any case.

There are differences among the replacement percentages and between both methods. So, the SCRC20M1 mix showed fulfilment of tv time at 15 min when the water or superplasticiser increases or the cement decreases. At 45 min, this concrete only satisfied the limits when the water increases, and at an age of 90 min the maximum time was no longer fulfilled for any variation. In the case of the SCRC20M3 mix, it also satisfied the limits at 15 min when the water or superplasticiser increases. However, at 45 min, this mix only showed fulfilment when the superplasticiser increases.

The SCRC50M1 mix only satisfied the target limits in the short term (at 15 min) when the water or superplasticiser increases or the cement decreases. The SCRC50M3 mix fulfilled the tv limits when the superplasticiser increases or decreases at an age of 15 min, and at 45 min only when the superplasticiser increases.

The 100% replacement concretes also showed some differences. The SCRC100M1 only satisfied the target limits when the superplasticiser or cement increases at 15 min. However, the SCRC100M3 only fulfilled the tv requirements when the water or superplasticiser increases at 15 and 45 min.

As can be seen, the tv parameter results are not conclusive enough, agreeing with many other authors that do not recommend the V-funnel test for workability control [KHAY08, WÜST03].

Relating to the L-box test (Table V-7, Figure V-34 and Figure V-38), the reference mix fulfilled the PL requirements for all variations at 15 and 45 min. At 90 min, the SCRC0 mix only satisfied the target limits when the water or superplasticiser increases. The 20% replacement concretes (SCRC20M1 and SCRC20M3) showed a PL parameter in agreement with the limits established up to 45 min. In the long term (90 min age), these mixes did not satisfy the limits, except for the SCRC20M1 mix with the water increase.

Table V-7. V-funnel and L-box test requirements

Mix	Age	tv - [5-25] s							PL - [0.8-1]						
	(min)	Base	W+	W-	S+	S-	C+	C-	Base	W+	W-	S+	S-	C+	C-
SCRC0	15	Y	Y	N	Y	N	Y	Y	Y	Y	Y	Y	Y		
	45	Y	Y	N	Y	N			Y	Y	Y	Y	Y		
	90	N	N	N	N	N			N	Y	N	Y	N		
SCRC20M1	15	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y	Y		
	45	N	Y	N	N	N			Y	Y	Y	Y	Y		
	90	N	N	N	N	N			N	Y	N	N	N		
SCRC50M1	15	N	Y	N	Y	N	N	Y	Y	Y	N	Y	Y		
	45	N	N	N	N	N			Y	Y	N	Y	Y		
	90	N	N	N	N	N			N	N	N	N	N		
SCRC100M1	15	N	N	N	Y	N	Y	N	Y	Y	N	Y	Y		
	45	N	N	N	N	N			Y	Y	N	Y	N		
	90	N	N	N	N	N			N	N	N	N	N		
SCRC20M3	15	Y	Y	N	Y	N			Y	Y	Y	Y	Y		
	45	N	N	N	Y	N			Y	Y	Y	Y	Y		
	90	N	N	N	N	N			N	N	N	N	N		
SCRC50M3	15	N	N	N	Y	Y			Y	Y	N	Y	N		
	45	N	N	N	Y	N			Y	Y	N	Y	N		
	90	N	N	N	N	N			N	Y	N	N	N		
SCRC100M3	15	Y	Y	N	Y	N			Y	N	N	Y	N		
	45	N	Y	N	Y	N			Y	N	N	N	N		
	90	N	N	N	N	N			N	N	N	N	N		

Note: Y: Yes, it meets the limits; N: no, it does not meet the limits

With regards to the 50% replacement concretes, the SCRC50M1 mix did not only fulfil the PL limits when the water decreases at 15 and 45 min, although at 90 min, this mix stopped being self-compacting regarding the requirements established for the PL parameter. The SCRC50M3 mix did not satisfy the target limits at 15 and 45 min when the water decreases, or when the superplasticiser decreases. At an age of 90 min, it only fulfilled the limits established when the water increases.

In the case of 100% replacement percentage, the SCRC100M1 mix presented the same behaviour as the SCRC50M1 mix. The SCRC100M3 mix only reached the PL minimum limit at an age of 15 min when the superplasticiser increases (as does the base mix at 15 and 45 min).

Regarding the J-Ring test, (Table V-8, Figure V-35, Figure V-39, Figure V-41 and Figure V-42), the target limits for the SFJ parameter were satisfied by the reference SCC (SCRC0) at all ages and for all variations.

The 20% replacement concretes (SCRC20M1 and SCRC20M3) satisfied the limits at 15 and 45 min, for both M1 and M3 methods. At an age of 90 min, the behaviour was different. The SCRC20M1 mix fulfilled the limits except when the superplasticiser decreases. The SCRC20M3 mix only fulfilled the limits when the water or superplasticiser increases. In the case of cement variations, the limits were satisfied in the long and short term with any variation.

The 50% replacement concretes satisfied the target limits at 15 and 45 min, no matter the variation introduced and independently of the working method (M1 or M3), with the only exception being the SCRC50M3 mix at 45 min for the decrease in water. However, at an age of 90 min, this mix stopped being self-compacting in all cases. With the M1 method the SCRC50 mix fulfilled the SFJ limits when the water or superplasticiser increases or cement decreases.

Table V-8. J-Ring test requirements

Mix	Age	SFJ - [610-850] mm							t500J - [2-5] s						
	(min)	Base	W+	W-	S+	S-	C+	C-	Base	W+	W-	S+	S-	C+	C-
SCRC0	15	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	45	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	90	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y
SCRC20M1	15	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	45	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	90	Y	Y	Y	Y	N	Y	Y	Y	Y	N	Y	N	N	Y
SCRC50M1	15	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	45	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y
	90	N	Y	N	Y	N	N	Y	N	N	N	N	N	N	N
SCRC100M1	15	Y	Y	N	Y	N	Y	Y	Y	Y	N	Y	N	Y	Y
	45	Y	Y	N	Y	N	Y	Y	N	Y	N	Y	N	N	Y
	90	N	N	N	N	N	N	N	N	N	N	N	N	N	N
SCRC20M3	15	Y	Y	Y	Y	Y			Y	Y	Y	Y	Y		
	45	Y	Y	Y	Y	Y			Y	Y	Y	Y	Y		
	90	N	Y	N	Y	N			N	Y	N	N	N		
SCRC50M3	15	Y	Y	Y	Y	Y			Y	Y	Y	Y	Y		
	45	Y	Y	N	Y	Y			Y	Y	N	Y	N		
	90	N	N	N	N	N			N	N	N	N	N		
SCRC100M3	15	Y	Y	N	Y	N			Y	Y	N	Y	N		
	45	Y	N	N	Y	N			N	N	N	N	N		
	90	N	N	N	N	N			N	N	N	N	N		

Note: Y: Yes, it meets the limits; N: no, it does not meet the limits

With regards to the 100% replacement concretes, the SCRC100M1 mix met the target limits at 15 and 45 min except when the water or superplasticiser decreases. At an age of 90 min, none of the modified mixes obtained from SCRC100M1 satisfied the SFJ requirements. In the case of the SCRC100M3 mix, it only satisfied the limits when the water (at 15 min) or superplasticiser (at 15 and 45 min) increases. At 90 min, it did not meet the minimum limit regarding the SFJ parameter for any variation.

Regarding the t500J parameter, the target limits were not satisfied by the reference SCC (SCRC0) at an age of 90 min when the water decreases. The SCRC20M1 mix did not meet the limits established for the t500J time at 90 min when the water or superplasticiser decreases or the cement increases. The SCRC50M1 mix met the t500J limits at 15 min in all cases. At 45 min, it did not satisfy the target limits, only when superplasticiser decreases. At an age of 90 min, it never fulfilled them. The SCRC100M1 mix did not satisfy the limits at 15 and 45 min when the water or superplasticiser decreases or at 45 min when the cement increases. At an age of 90 min, this mix stopped being self-compacting regarding the t500J limits for any variation.

With regards to the M3 method, the SCRC20M3 mix always satisfied the t500 target limits at 15 and 45 min. At 90 min, it only fulfilled them when the water increases. The SCRC50M3 mix met the requirements at 15 min regardless of the variation introduced. At 45 min, the mixes where the water or superplasticiser decreases did not fulfil the target limits of t500J and the same happened with any variation at 90 min. Finally, the SCRC100M3 mix only satisfied the t500J limits when the water or superplasticiser increases as occurred with the SFJ parameter. At 45 and 90 min, it did not fulfil the maximum time for any variation.

Regarding the PJ parameter of the J-Ring test (Figure V-36, Figure V-40 and Figure V-42), the SCRC0 mix satisfied the target limits at 15 and 45 min when the water or superplasticiser increases or the cement decreases. This parameter had already been adjusted in the reference concrete ("Rheology" phase) on the upper limit. Then, SCRCs hardly satisfied the PJ target limits when variations were introduced. Thus, only the SCRC20M1 mix fulfilled the maximum limit established at an age of 15 min when the water increases and at 15 and 45 min when the superplasticiser increases.

Finally, with regards to the sieve segregation test (Figure V-36, Figure V-40 and Figure V-42), all mixes (independently of the replacement percentage and the variation, water, superplasticiser or cement content) fulfilled the target limits for the SR parameter.

To sum up, regarding workability tests, the slump flow and J-Ring tests were found to be sensitive for robustness evaluation [NAJI11]. Based on the experience obtained during this research, it could be suggested to combine the SF and t500 parameters (slump flow test) to evaluate the filling ability, the PL and t500J parameters (L-box and J-Ring tests respectively) to assess the passing ability, and the SFJ parameter (J-Ring test) to describe the filling capacity. These tests have been shown to be stable and quite insensitive to the operator and external conditions.

With regards to the robustness analysis, it has been seen that the variations affecting the self-compactability of SCRC to a greater extent are: the water decrease, superplasticiser decrease and cement increase.

With regards to the robustness of the different recycled concretes it can be concluded that the reference SCC (SCRC0) showed a robust behaviour. This concrete presented good filling ability, passing ability and filling capacity.

The analysis of SCRCs with low replacement percentages, 20%, and for both mixing methods, M1 and M3, showed a similar and robust behaviour up to an age of 45 min when analysing all three workability characteristics (filling ability, passing ability and filling capacity). This can also be said for the filling ability at an age of 90 min. However, regarding the passing ability and the filling capacity, the mix produced with the M3 method showed some more difficulties maintaining its self-compacting condition than that produced with the M1 method.

The mixes with 50% of RCA and produced with both the M1 and M3 methods kept their self-compacting behaviour until an age of 45 min. Regarding their filling ability and passing ability, they showed similar behaviour at all ages. Regarding their filling capacity, these concretes also had similar behaviour at 15 and 45 min, although in the long term the filling capacity of the mix produced with the M3 method was more negatively affected than that produced with the M1 method.

When the 100% replacement concretes are analysed, it can be seen that, regarding filling ability, passing ability and filling capacity at 15 and 45 min, SCRC made with M1 maintains self-compacting behaviour better than those made with the M3 method. At the age of 90 min, their behaviours (M1 and M3 methods) were no longer self-compacting. Actually, in the case of the M3 method, the mix had already lost its self-compacting condition for most of variations in the short term (15 min).

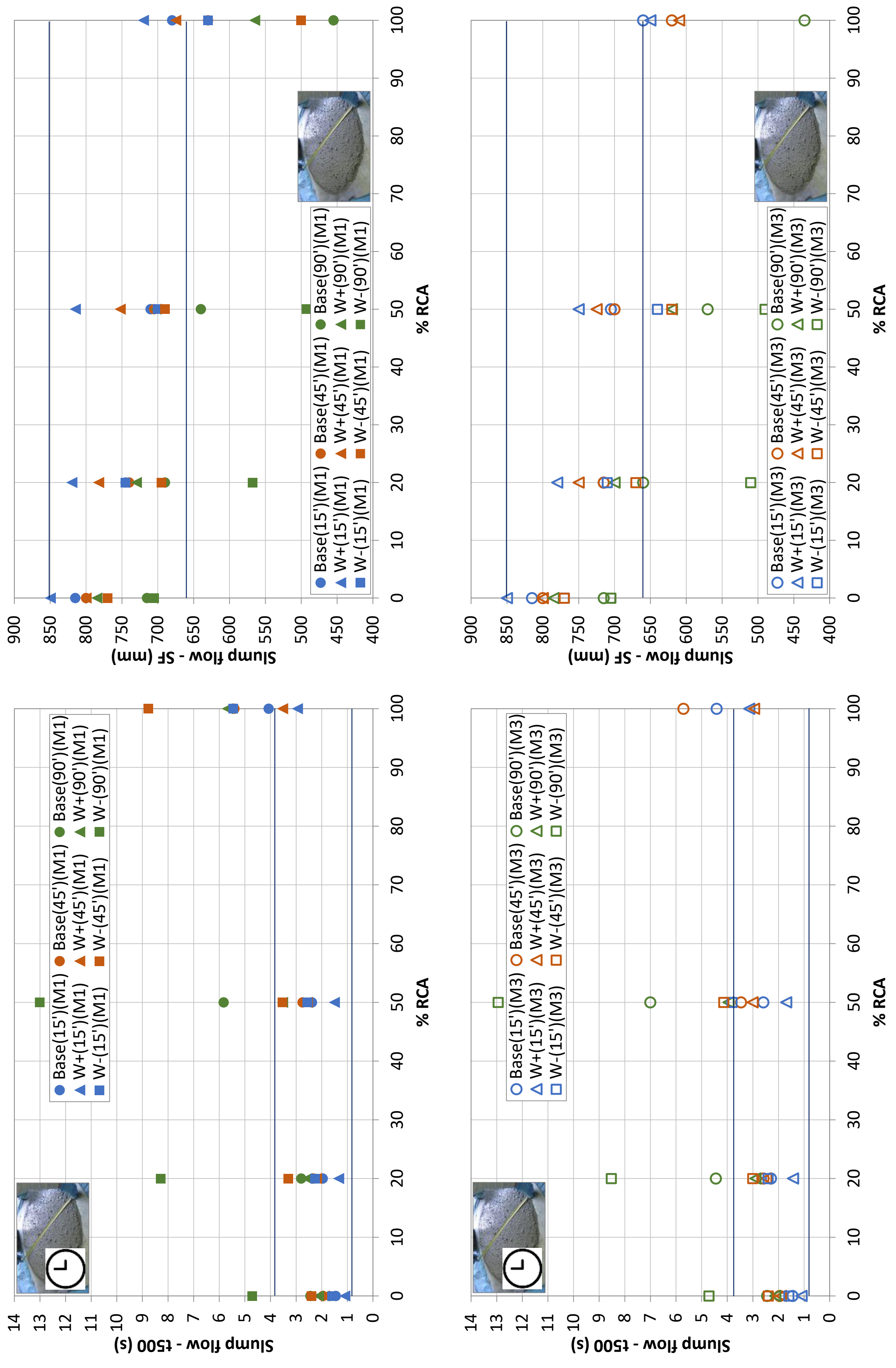


Figure V-33. Slump flow test (SF and t500 parameters). Water variations

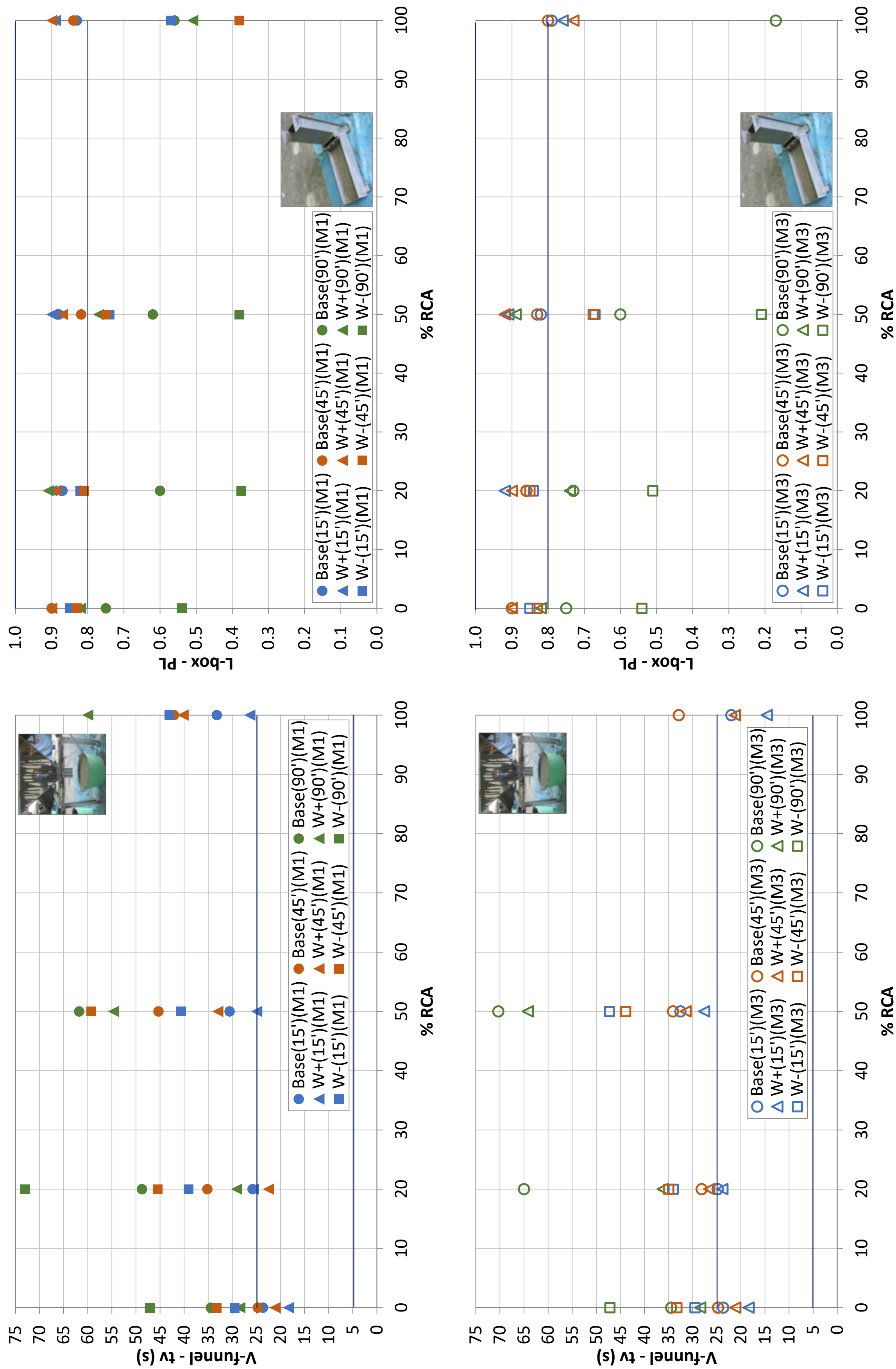


Figure V-34. V-funnel and L-box tests (tv and PL parameters). Water variations

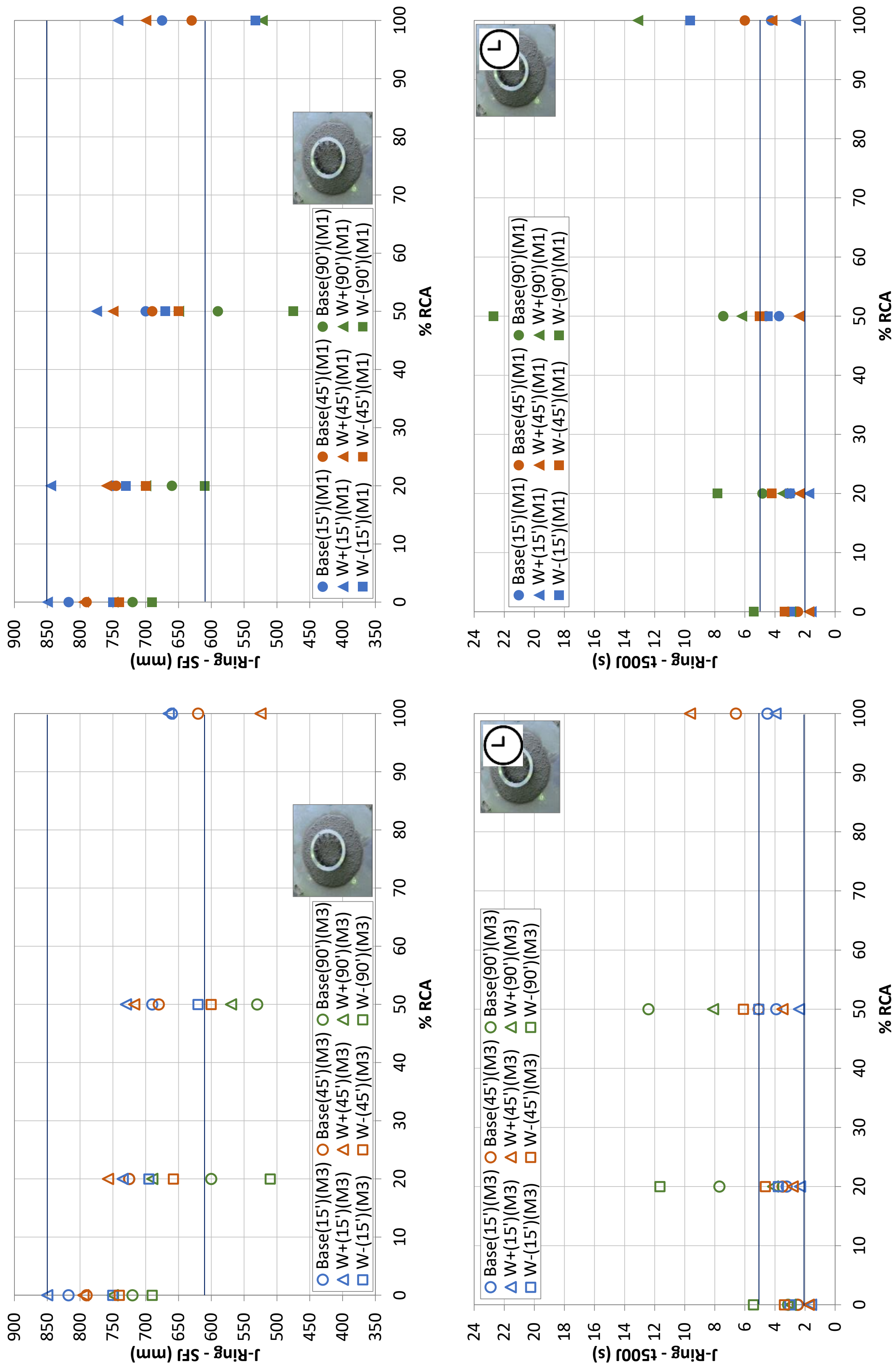
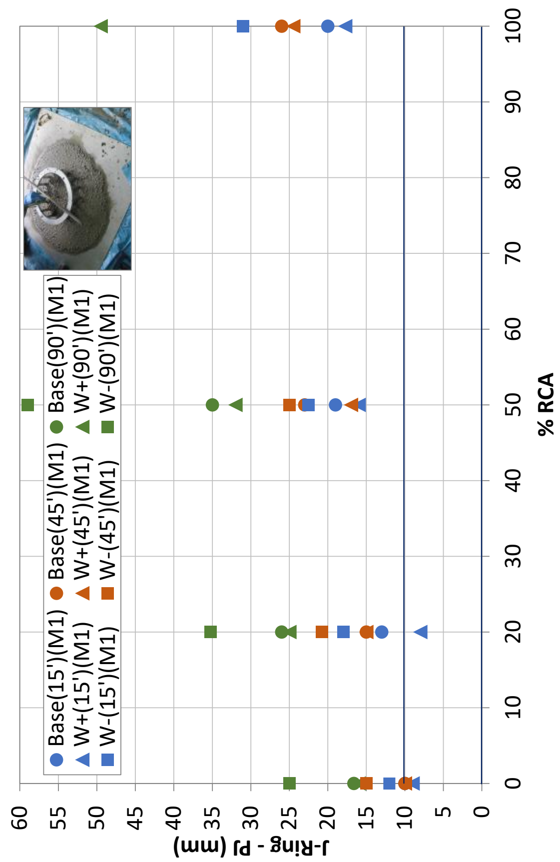
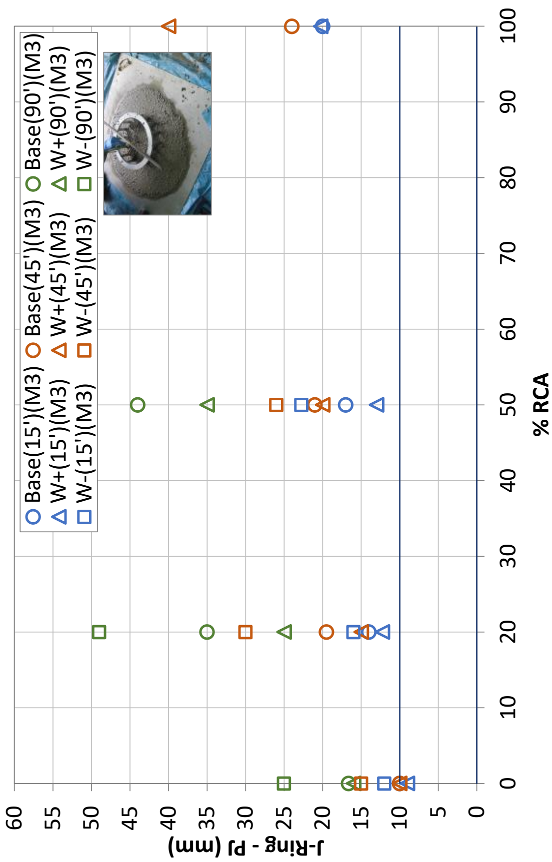


Figure V-35. J-Ring test (SFJ and t500J parameters). Water variations





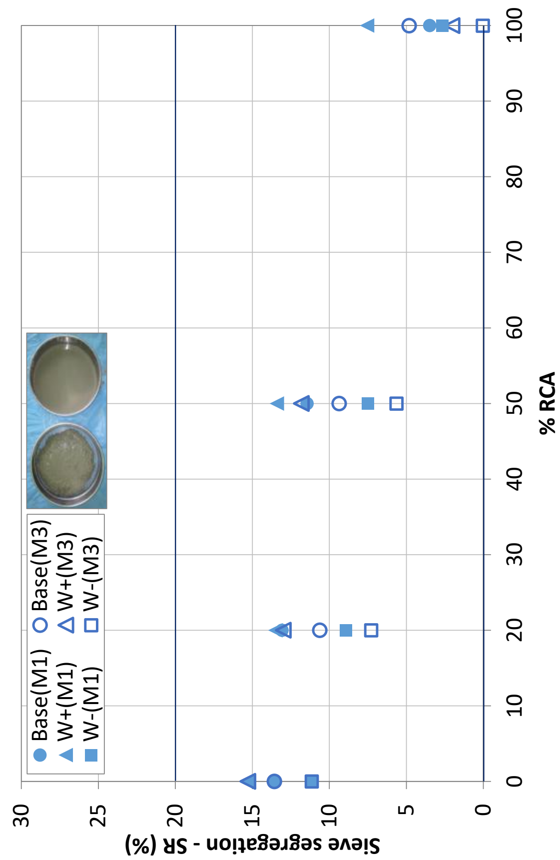


Figure V-36. J-Ring and sieve segregation tests (PJ and SR parameters). Water variations

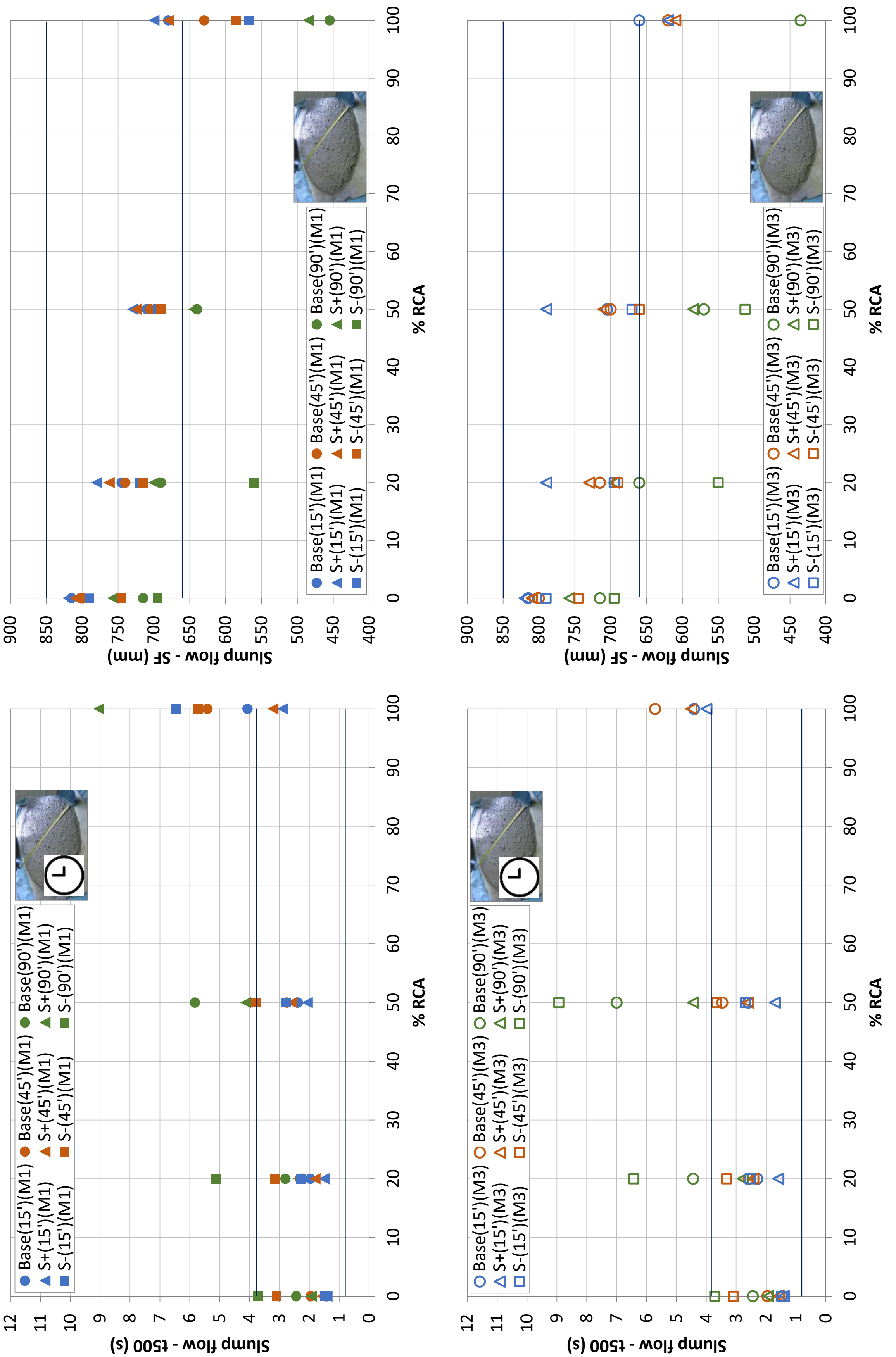


Figure V-37. Slump flow test (SF and t500 parameters). Superplasticiser variations

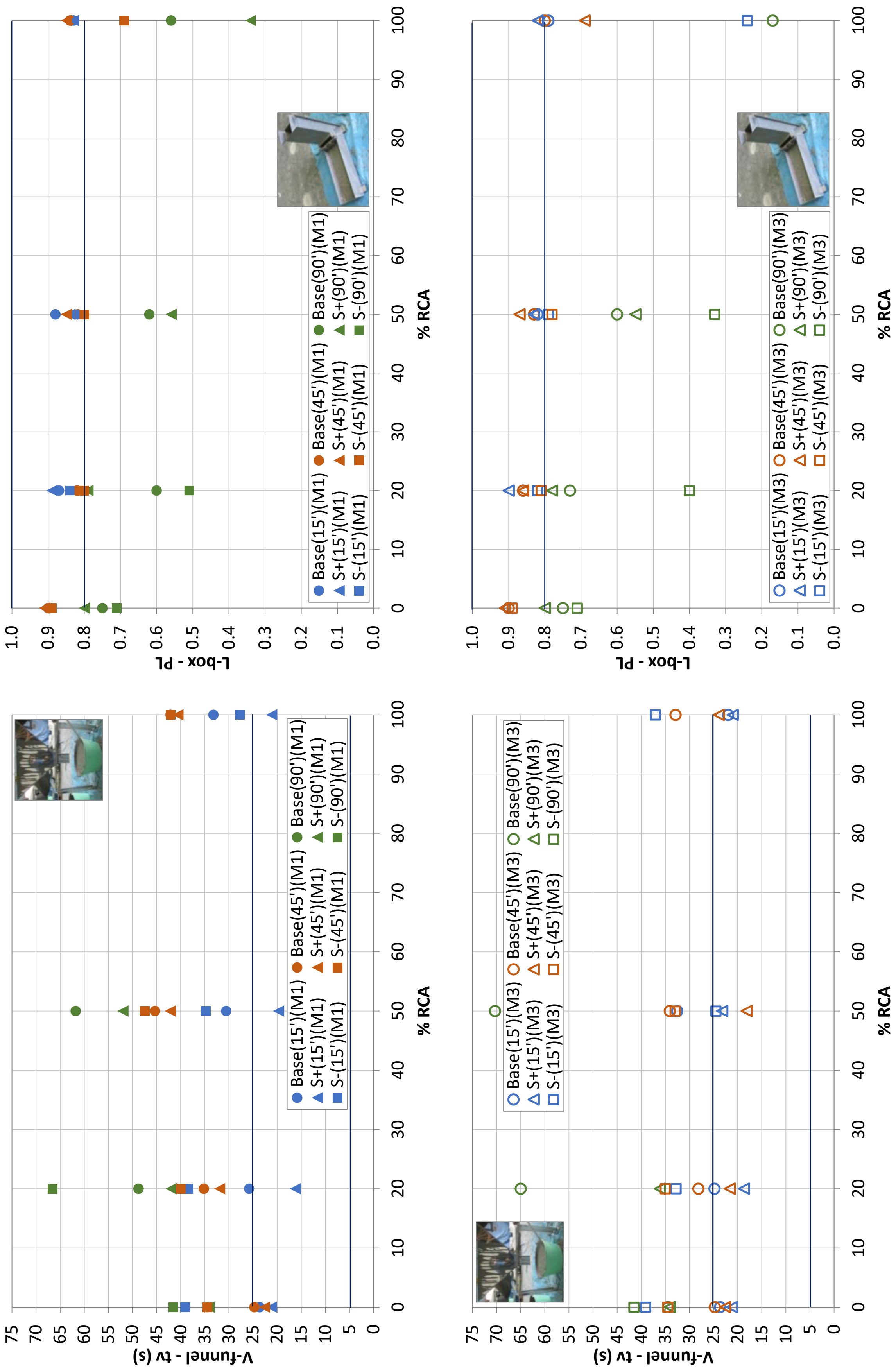


Figure V-38. V-funnel and L-box tests (tv and PL parameters). Superplasticiser variations

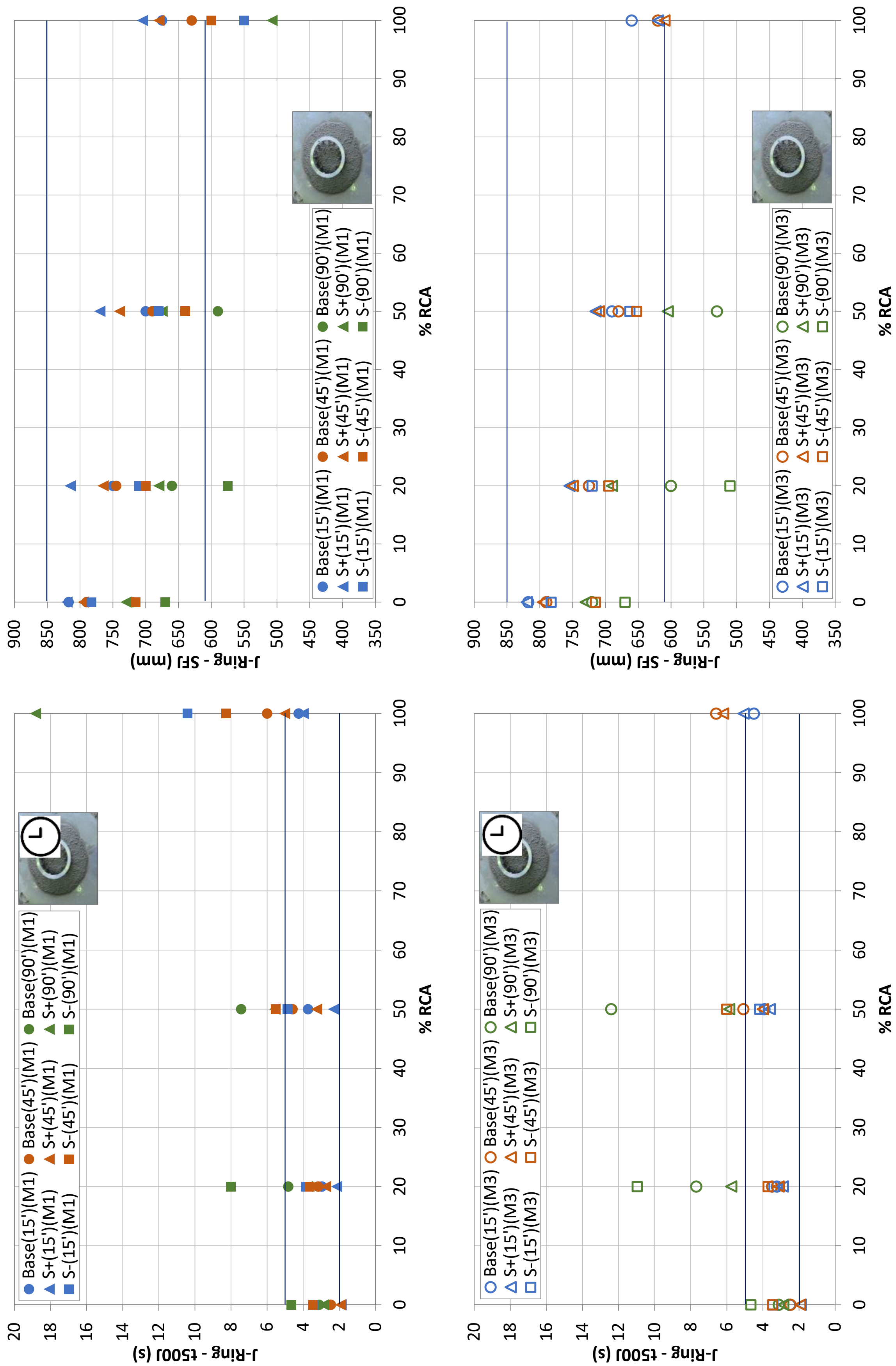


Figure V-39. J-Ring test (SFJ and t500J parameters). Superplasticiser variations

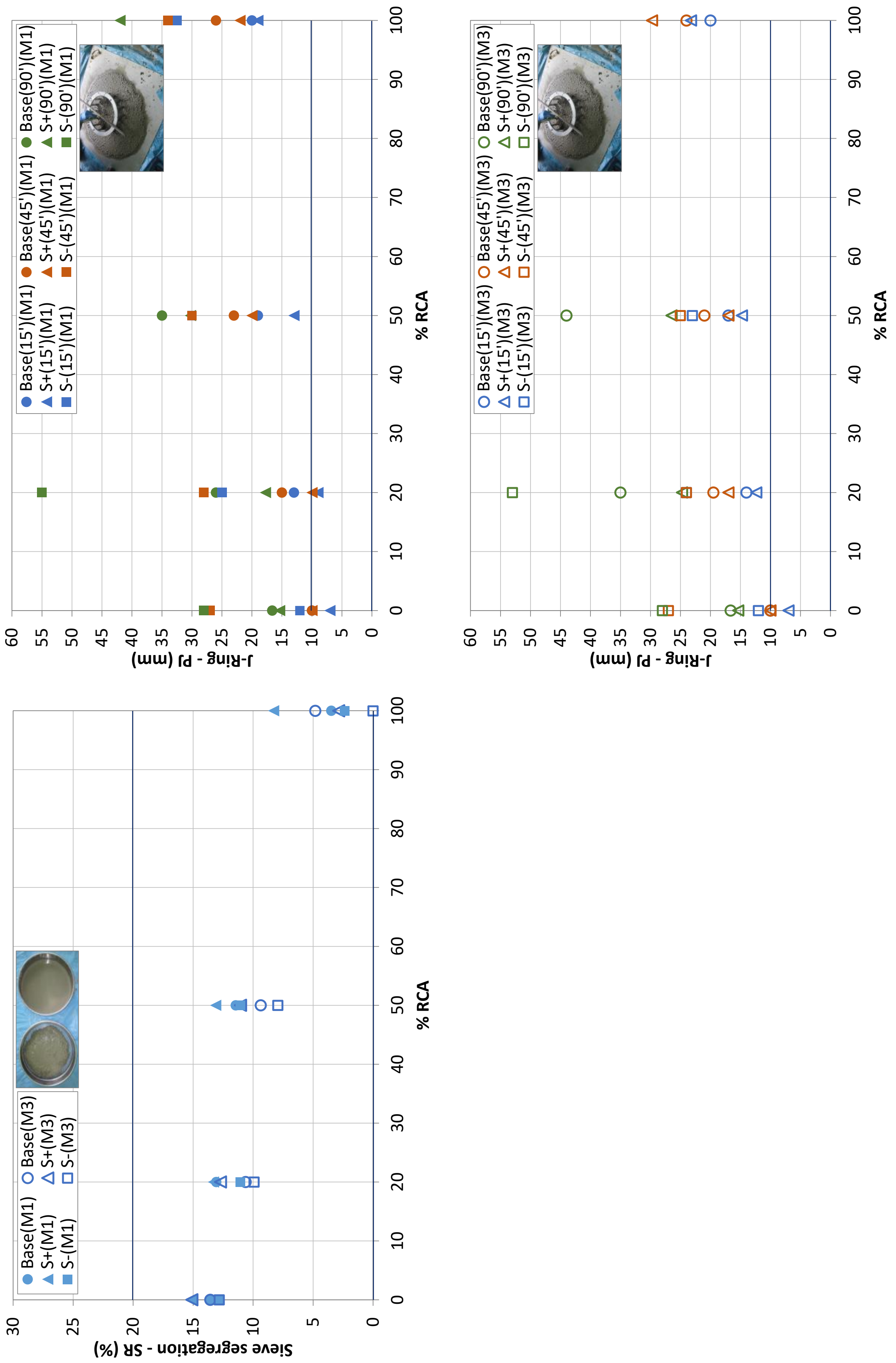


Figure V-40. J-Ring and sieve segregation tests (PJ and SR parameters). Superplasticiser variations

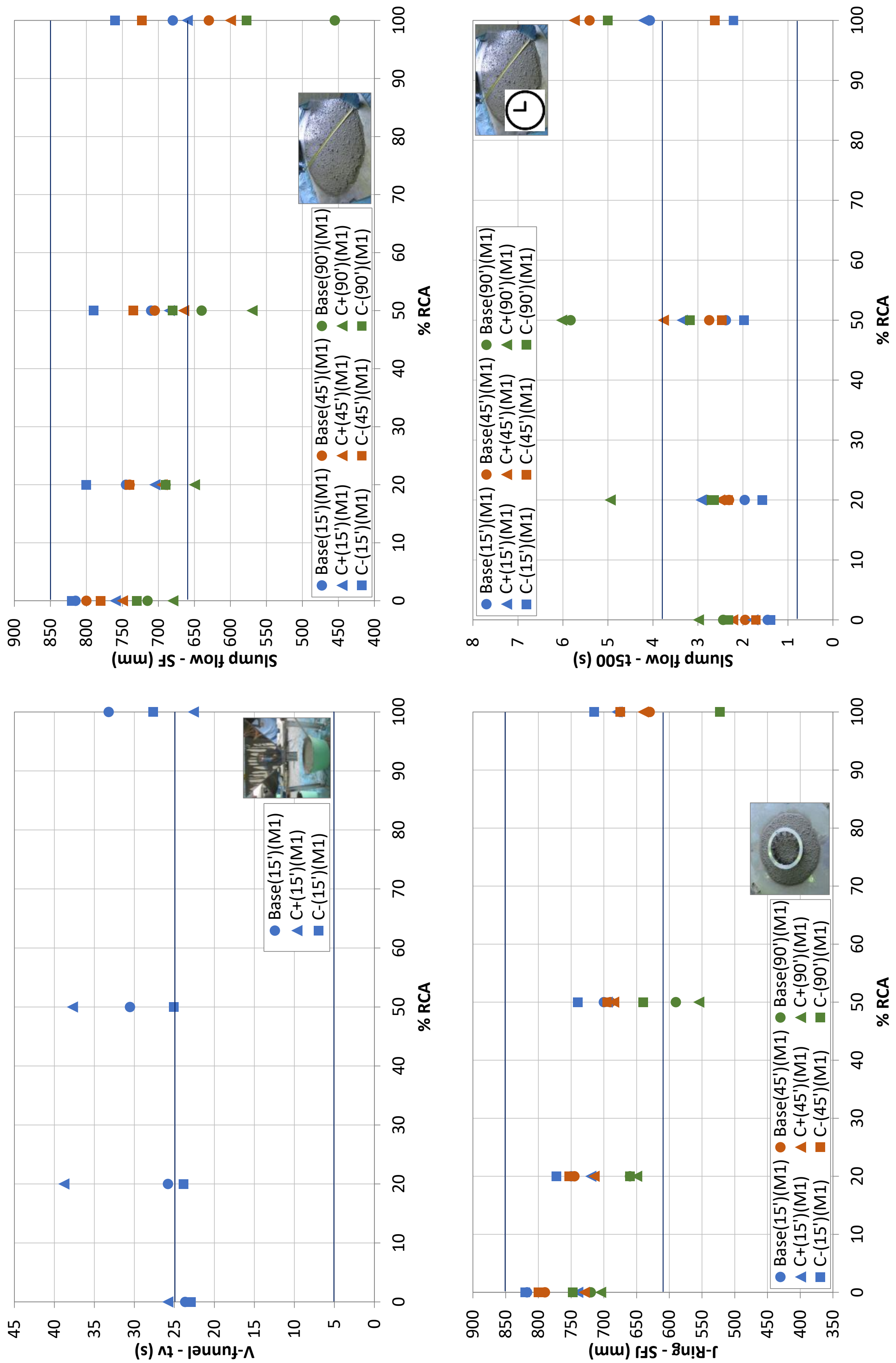


Figure V-41. Slump flow, V-funnel and J-Ring tests (SF, t500, tv and SFJ parameters). Cement variations

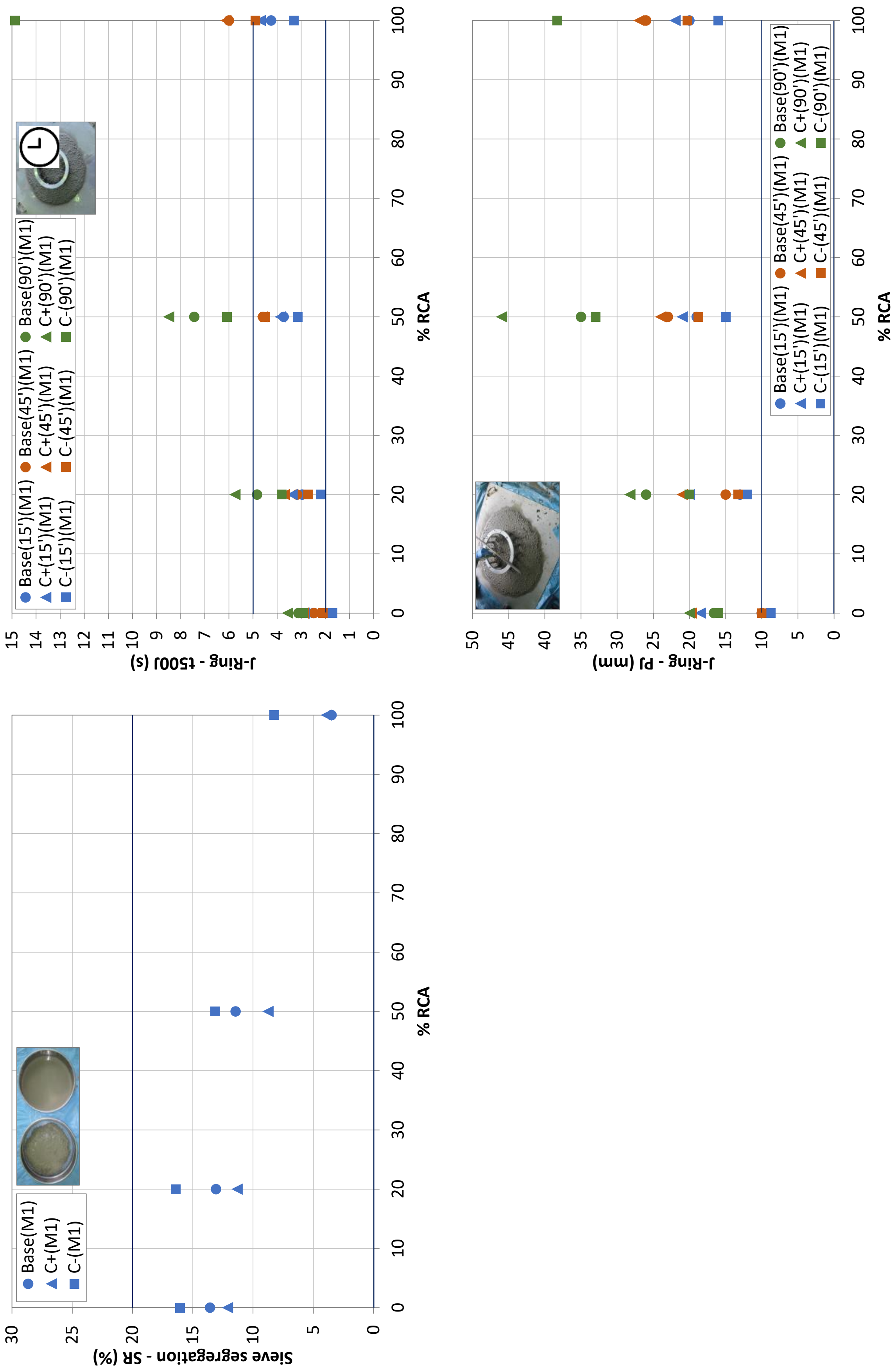


Figure V-42. J-Ring and sieve segregation tests (t500J, PJ and SR parameters). Cement variations

Definitively, in general terms, SCRC with low replacement percentages (20% and 50%) were robust mixes up to an age of 45 min. In the case of 100% SCRC, the design of a robust mix is more difficult, and even more so when a recycled coarse aggregate with a previous moisture content (M3 method) is used. This lead to greater difficulty in controlling workability than when using recycled aggregates in dry-state conditions (M1 method).

4.2 Study of robustness with rheological tests

This analysis is focused on the measurement of static yield stress and plastic viscosity development over time with SCRC mixes.

Again, in this case, it can be seen that mixes with low replacement ratios are more robust than those produced with high replacement ratios, i.e. they maintain the rheological parameters over time without hardly any variations. Moreover, the mixes produced with the M1 method (dry aggregate) are more robust than those produced with the M3 method (recycled aggregate with 3% natural moisture) (Figure V-43, Figure V-44, Figure V-45 and Figure V-46).

Figure V-43 shows that the greatest influence of water variation on self-compactability takes place when the water is reduced and the replacement percentage is high. Furthermore, this is more noticeable in the M3 method, where it is more difficult to control the water content due to the moisture in the recycled aggregate.

Secondly, yield stress is not significantly modified by changes in the dosage of superplasticiser when dry-state recycled aggregate is used (Figure V-44). Therefore, in this case, all SCRCs show suitable rheological behaviour, similar to conventional SCC up to a mix age of 45 min. This trend can also be seen in the M3 method (Figure V-44), but only up to 50% of RCA.

Finally, Figure V-45 and Figure V-46 show the results obtained with cement modifications, which follow the same trend as those obtained with the water variations (therefore, only the M1 method was studied). Thus, an increase in cement will be analogous to a decrease in water and vice versa. Although, the water changes influence the SCRC behaviour to a greater extent.

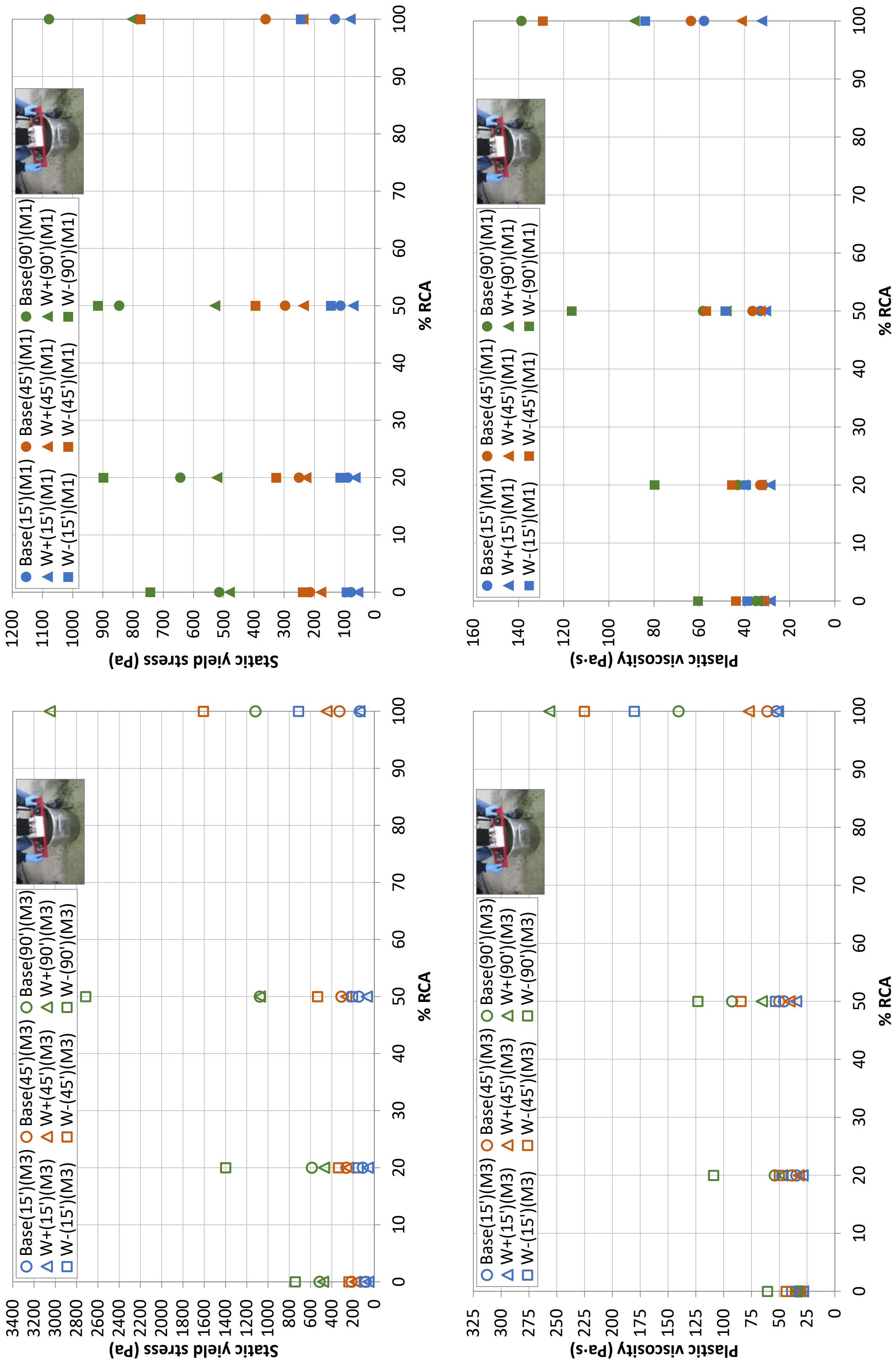


Figure V-43. Static yield stress and plastic viscosity. Water variations

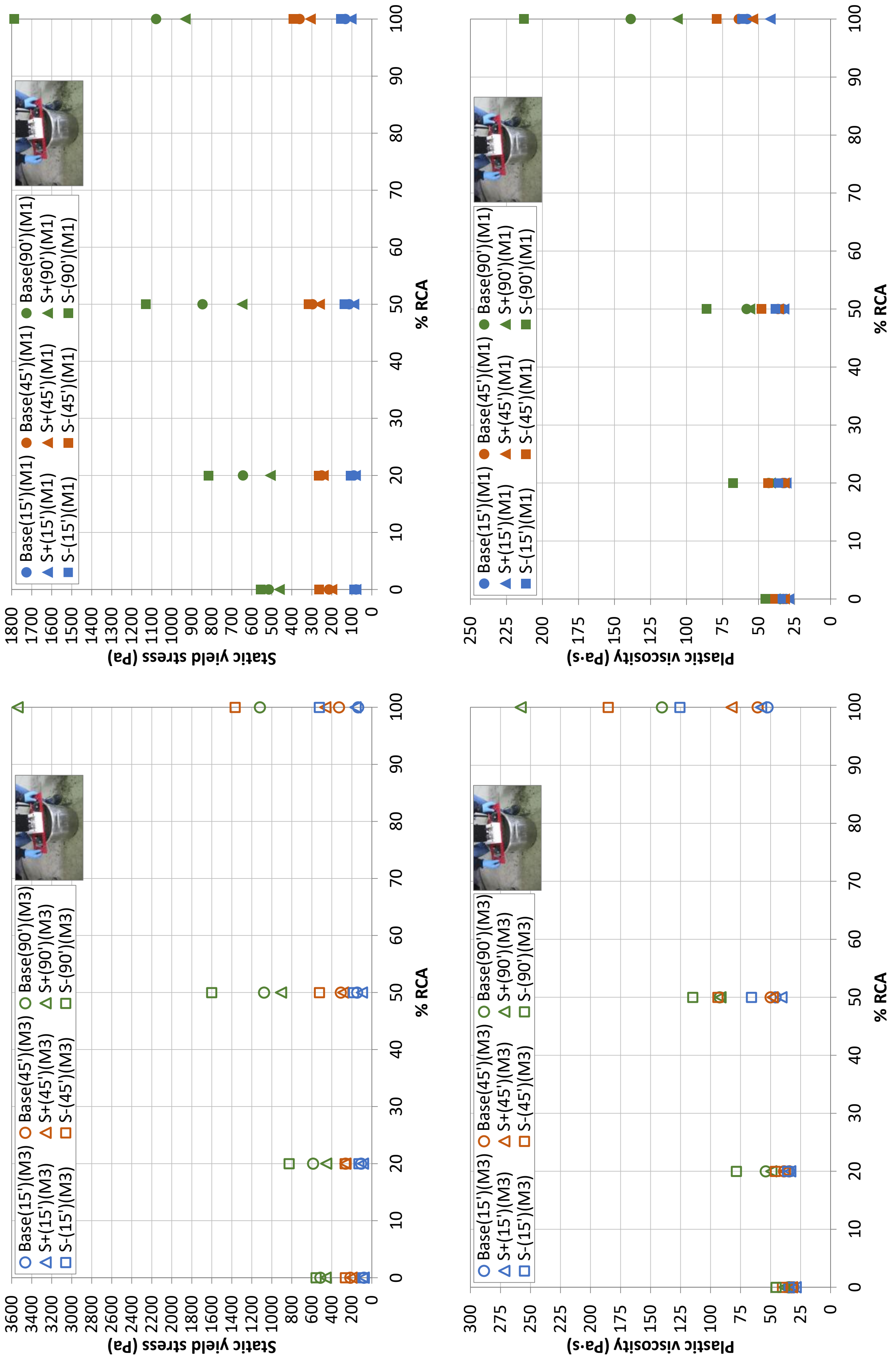


Figure V-44. Static yield stress and plastic viscosity. Superplasticiser variations

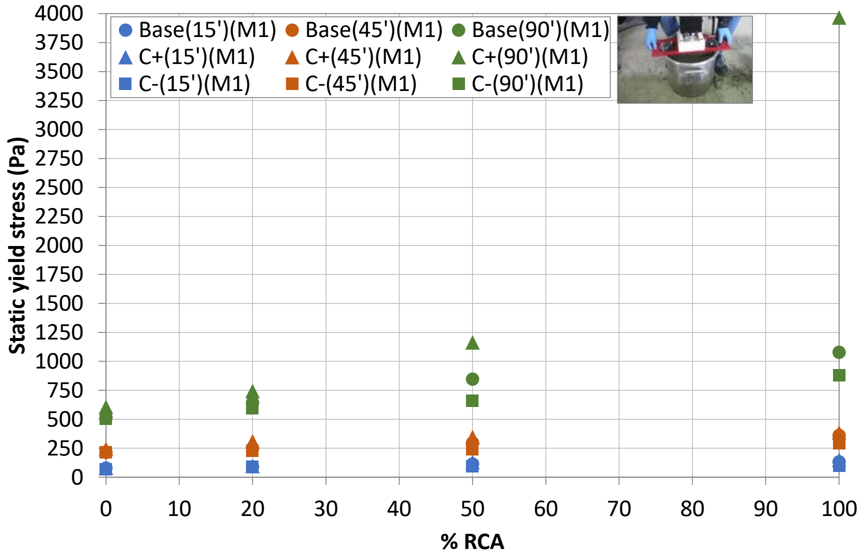


Figure V-45. Static yield stress. Cement variations

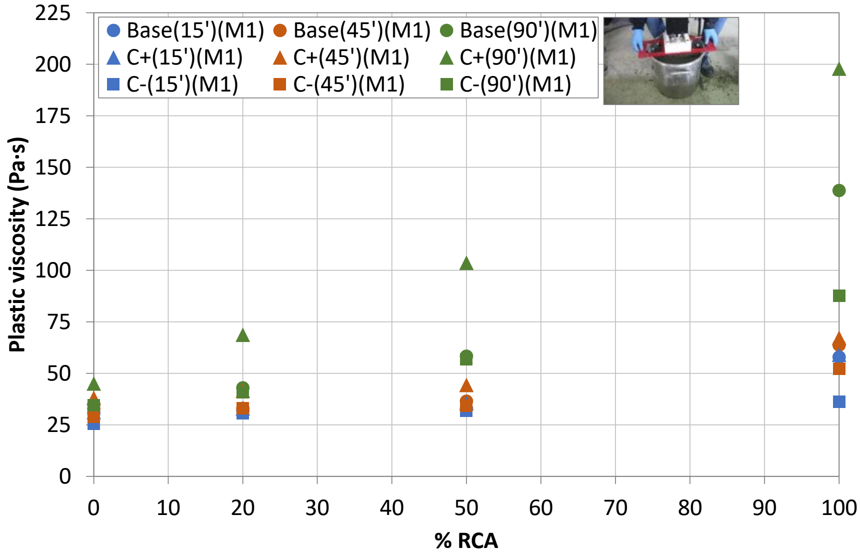


Figure V-46. Plastic viscosity. Cement variations

5 CONCLUSIONS

In this chapter, results about rheology and robustness of self-compacting concrete incorporating recycled concrete coarse aggregate (SCRC) were presented. The effect of its incorporation on fresh-state concrete properties over time was shown.

Based on the results obtained, the following conclusions can be drawn about workability and rheology of the studied mixes:

- The rheological tests are the most stable tests to evaluate SCRC fresh-state behaviour. The empirical tests are more dependent on the sensitivity of the operator, especially when the parameters of time are measured. In this sense, the V-funnel test results are not conclusive enough, agreeing with many other authors who do not recommend it for workability control. Also, the PJ parameter of J-Ring test is found not to be well correlated with the other results.

- The production of recycled concrete (20%, 50% and 100% of recycled coarse aggregate) adding extra water to compensate the high water absorption of recycled aggregate does not involve significant changes in fresh-state behaviour (comparing with 0%) up to 45 min. When the results obtained at 90 min are analysed, the workability loss is more significant, especially for the total replacement. Up to 20%, the fresh behaviour is guaranteed even up to a mix age of 90 min. Then, it has been demonstrated that concrete with the 20% of RCA tends to present a similar behaviour to that of the control concrete.
- The analysis of M1 (dry aggregate) and M3 (aggregate with a 3% of natural moisture) mixing procedures indicates that the use of the recycled coarse aggregate with a previous moisture content involves the greatest difficulty in workability control, especially for high recycled aggregate ratios (50% and 100%). Regarding the M2 method, although the concretes made with this method tend to satisfy the target limits, their tendency towards segregation is evident for high replacement percentages. Moreover, from an industrial point of view, this method is unfeasible due to the pre-soaking time required being too high when the quantities of recycled aggregate increase. Therefore, it would not be advisable to produce SCRC with replacement percentages above 20%.

On the other hand, according to the robustness results, the conclusions are as follows:

- With regards to robustness results, it was seen that the variations that provide the greatest fresh behaviour changes are those affecting water. Moreover, and regarding the tests suitability, it can be suggested to combine the SF and t500 parameters (slump flow test) to evaluate the filling ability, the PL and t500J parameters (L-box and J-Ring tests respectively) to assess the passing ability, and the SFJ parameter (J-Ring test) to describe the filling capacity. These tests have been shown to be stable and quite insensitive to the operator and external conditions. All the rheological tests provide suitable information about concrete fresh behaviour.
- With regards to recycled concrete behaviour, it was seen that concretes with a replacement of 20% maintain their self-compacting nature in both the long and short term. Replacements of 50% guarantee the self-compacting ability up to 45 min for both the M1 and M3 methods. Finally, concretes with total substitution and produced with the M1 method stop being self-compacting after 45 min, with this time being reduced to 15 min with the M3 method.
- These results confirm that the mixes produced with low replacement ratios and using the M1 method are more robust than those produced with the M3 method. The use of recycled aggregate with 3% moisture (M3) involves a robustness loss that can prevent some empirical tests from being carried out in some cases. These same results are clearly confirmed with the rheological tests.

CHAPTER VI
Analysis of self-compacting recycled concrete fresh behaviour: Workability and Rheology

1 INTRODUCTION AND OBJECTIVES

In the previous chapter, results about the time-dependent rheological behaviour and the robustness of self-compacting recycled concrete (SCRC) were shown. In this chapter the analysis of the rheological test results is made with three objectives. The first one is to corroborate that the relationships between empirical parameters and between empirical and rheological ones show the same tendency in conventional and recycled self-compacting concretes, and to use a workability box to define a suitable SCRC fresh behaviour.

On the other hand, the second objective is to show that the specificity of SCRC rheology lies in the quantity of extra water necessary to compensate the recycled aggregate absorption during the mixing protocol, which affects the effective water to cement ratio, and in the intrinsic characteristics of recycled coarse aggregate that modifies the solvent composition of the concrete. Finally, the third objective is to know how the rheological behaviour of SCRC evolves over time.

Table VI-1 shows which results have been used to carry out the analysis that leads to the achievement of the aforementioned objectives.

Table VI-1. Results used in the analysis of SCRC workability and rheology

Objective	Mixes	Mixing methods	Testing times
Relationships between empirical and rheological parameters	“Rheology” and “Robustness” mixes	M1, M3, 20M2	15 and 45 min
Rheological behaviour of SCRC at 15 min	“Rheology” and “Robustness” mixes	M1	15 min
Rheological behaviour of SCRC over time	“Rheology” and “Robustness” mixes	M1	15, 45 and 90 min

To achieve the first objective, the analysis focuses on the “Rheology” and “Robustness” of the mixes at 15 and 45 min. Results at 90 min were not used in this first analysis because, as seen in Chapter V, workability loss is significant at this age, especially for mixes with total replacement ratios. Regarding mixing methods, since concretes made with the M2 method showed a tendency to segregation for high replacement percentages, only the SCRC20M2 mix is used in this analysis.

To analyse the rheological behaviour of SCRC, results at 15 min of mixes made with M1 method are used. In this case, mixes with the water variations joined to the baseline mixes offer a suitable range to study the fundamental rheological behaviour of SCRC. Finally, the influence of different materials variations on SCRC rheological behaviour are studied using “Robustness” mixes produced with M1 method and collecting results at 15 min.

To develop the analysis of rheology over time, results at 15, 45 and 90 min of “Rheology” mixes made with M1 method are used. Results at 15, 45 and 90 min obtained with “Robustness” mixes are employed to confirm this analysis.

Mixes made with M2 and M3 methods are not used in both these analyses due to segregation, detected in M2 mixes, as well as the difficulty of water control, produced in M3 mixes.

2 RELATIONSHIPS BETWEEN EMPIRICAL AND RHEOLOGICAL PARAMETERS IN SCC AND SCRC

In this section, the key idea is to determine if the relationships between parameters of both workability and rheology of self-compacting recycled concrete (SCRC) are similar to the ones of conventional self-compacting concrete (SCC). To do so, the relationships between different empirical parameters and between empirical parameters and rheological properties obtained in SCRC have been compared with those of conventional self-compacting concrete.

Rheological theory holds that flow is a function of two parameters, in ordinary language, extent of flow and rate of flow. In self-compacting concrete, empirical tests can give us information on both. Actually, it is known that the former is expressed by slump flow and the latter by any of the timed tests. Therefore, in the literature, different graphs regarding yield stress and plastic viscosity versus different individual empirical parameters were represented, and possible correlations were established [TEST04]. This means that empirical parameters can give accurate information on rheological properties, yield stress and plastic viscosity.

Analysing the results achieved in the literature [KOEH03], it can be concluded that some empirical parameters are related with yield stress while others correlate better with plastic viscosity.

Regarding yield stress, in the literature [TEST04], a strong relationship of this property with the slump flow value was found (SF) as well as with the L-box ratio (PL), obtaining a R^2 of 0.76 and 0.73, respectively. This work [TEST04] also studied the correlations of yield stress with other empirical parameters obtaining results that were not so strong, with R^2 under 0.4.

Other authors [ROUS06c] state that, for homogeneous yield stress fluids, the L-box test result only depends on its yield stress. In this case, it has been emphasized that the L-box gate should be opened (lifted) slowly instead of promptly. Otherwise, the test result depends on a combination of the intrinsic properties of the sample (yield stress, plastic viscosity, density) and external parameters (gate lifting rate for example).

Also, in the literature [TEST04], different relationships involving plastic viscosity have been found. Firstly, a rather good relationship (with an R^2 of 0.76) with t500 (from the slump flow test) has been found. Hence, it can be concluded that the two parameters measured in the slump flow test, SF (horizontal flow diameter) and t500 (the time needed to reach 500 mm flow) maintain a certain degree of independence.

Concerning the relationship of plastic viscosity with the flow time of the V-funnel test, a reasonably good R^2 coefficient was found, about 0.6. Finally, the relationship with the slump flow value (SF) and the L-box ratio (PL) seems to be rather poor.

Therefore, it can be argued that SF and PL are related to yield stress, while t500 and tv are related to plastic viscosity. In parallel, it is expected that t500J is related to plastic viscosity, and SFJ and PJ to yield stress.

Figure VI-1 summarizes these relationships. According to this figure, there has to be some kind of relationship between the parameters that inform about yield stress and, in the same regard, the parameters that inform about plastic viscosity also have to be related.

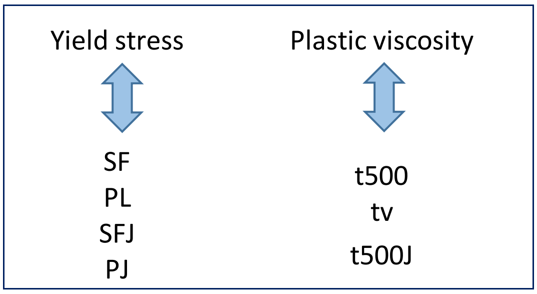


Figure VI-1. Relations between rheological and empirical parameters

2.1 Relationships between empirical parameters

Relationships for self-compacting recycled concrete (“Rheology” and “Robustness” mixes) were obtained between the empirical parameters (at a mix ages of 15 and 45 min) that correlate with the same rheological property. This means, regarding yield stress, that the following relationships were analysed: SF with PL (Figure VI-2), SF with PJ (Figure VI-3), SF with SFJ (Figure VI-4), PJ with PL (Figure VI-5), SFJ with PL (Figure VI-6) and SFJ with PJ (Figure VI-7). Concerning plastic viscosity, the t500 with t500J (Figure VI-8) relationship was studied. The time of the V-funnel test was disregarded for not being a good parameter to characterize the fresh behaviour of a SCRC mix (Chapter V and [HWAN06]). In this manner, it was not considered to further develop this analysis.

Table VI-2 presents the coefficients of determination, R^2, obtained for each relationship. In all cases the value of R^2 indicates a good correlation, with a value of 0.7 or higher. The best R^2 coefficients were obtained correlating the parameters of the slump flow test with the ones of the J-Ring test, i.e. SF with SFJ, SF with PJ and SFJ with PJ. This fact can be attributed to the geometric relationship that exists between these test devices [WÜST03].

Table VI-2. R^2 coefficients in relationships between empirical parameters

Relationship	SF-PL	SF-PJ	SF-SFJ	PJ-PL	SFJ-PL	SFJ-PJ	t500-t500J
R^2	0.70	0.81	0.87	0.70	0.69	0.80	0.75

Although it is known that each parameter is related to a specific fresh property (filling ability, passing ability, filling capacity and segregation resistance), the strong relationship between all of them indicates that it is difficult to assess them independently. For example, the slump flow test describes filling ability, while the L-box test has been designed to evaluate passing ability. The strong relationship between SF and PL indicates that it is difficult to assess blocking (PL) independently of flow (SF). Despite this fact, as each of them deal with one fresh property, both parameters are needed to describe SCC fresh behaviour.

In all figures (Figure VI-2, Figure VI-3, Figure VI-4, Figure VI-5, Figure VI-6, Figure VI-7 and Figure VI-8), results of SCRC appear in blue and results of conventional SCC (in this work SCRC0) are drawn in red. According to these figures, the first conclusion that can be drawn is that SCRC shows the same tendency as conventional SCC in all relationships.

Analysing each particular relationship, the Figure VI-2 shows that the PL index increases with the SF parameter. A PL ≥ 0.8 (the minimum required for self-compacting behaviour [EN206-9]) is easily achieved if there is high flow (SF≥ 660 mm). In the same way, the L-box blocking ratio that corresponds to the minimum slump flow required for a SCC (550 mm) [EN206-9] is found to be 0.72. Therefore, all mixes with high slump flow values have exhibited a good passing ability measured with the L-box test.

In Figure VI-3, the relationship between SF and PJ parameters can be seen. The PJ parameter decreases with the increase in slump flow. However, the minimum SF value that corresponds to the limit established for the PJ parameter (10 mm [EN206-9]) is of about 800 mm, very far from the minimum slump flow required for a SCC (550 mm). In the same way, the PJ maximum value that corresponds to the minimum slump flow required for a SCC (550 mm) is 35 mm and the one related to a SF of 660 mm (the minimum value required in most of the SCC applications [EN206-9]) is determined to be about 25 mm. According to this relationship, the 10 mm maximum limit of PJ is quite strict to describe the ability of SCRC to flow through highly restricted areas (passing ability).

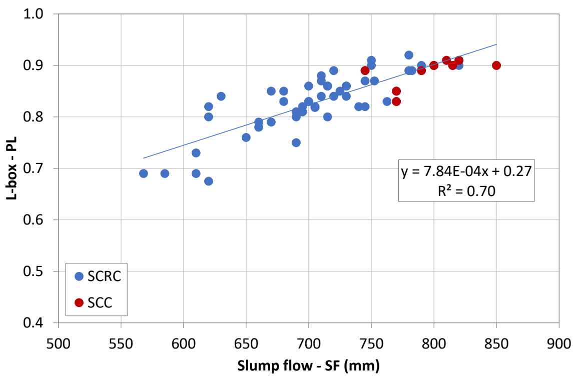


Figure VI-2. Relationship between SF (slump flow) and PL (L-box)

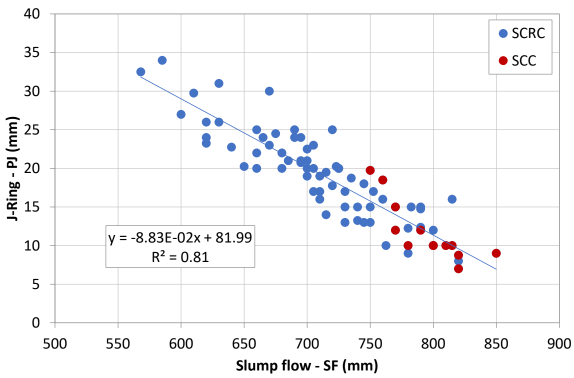


Figure VI-3. Relationship between SF (slump flow) and PJ (J-Ring)

A very good correlation between SF and SFJ was obtained (Figure VI-4) with a R^2 coefficient of 0.87. A SF ≥ 550 mm would correspond, also, to a SFJ value ≥ 550 mm. There seems to be a direct correlation between both parameters. In fact, the minimum SFJ value of 610 mm established in Chapter V would correspond to a SF value of about 610 mm. Then, all SCRC mixes with high slump flow values exhibited a good filling capacity (filling ability plus passing ability) measured with the J-Ring test (SFJ parameter). This means that mixes with high slump flow (high flowability) are able to show high J-Ring flow, being SF and SFJ equal or very similar.

In Figure VI-5, blocking measured with the J-Ring test (PJ) was compared directly to blocking obtained from the L-box test (PL). The PJ parameter increases with the decrease in the PL parameter. Again in this case, the minimum PL value that corresponds to the limit established for the PJ parameter (10 mm [EN206-9]) is about 0.9, different from that required for a SCC (PL ≥ 0.8). In the same way, the PJ value that corresponds to the minimum PL required for a SCC, is about 25 mm. Therefore, it can be said that fulfilling the passing ability measured with the PL parameter most of the mixes do not accomplish with the PJ parameter (that also represents passing ability).

This result along with the one obtained from the relationship between SF and PJ parameters and with the opinion of other authors [TEST04], leads to the conclusion that more site information and experience is required to confirm the practical value of the proposed PJ limit for quality control and mix design purposes. In this work, according to both the relationship PJ-PL and SF-PJ, a suitable limit for the PJ parameter could be 25 mm. With PJ ≤ 25 mm, the limit of PL (PL ≥ 0.8) and the recommended value of SF (SF ≥ 660 mm) can be fulfilled without any problem.

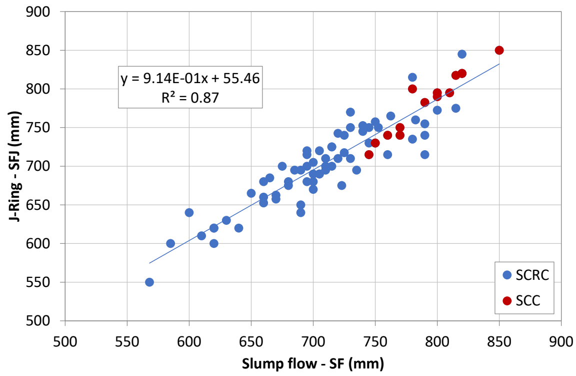


Figure VI-4. Relationship between SF (slump flow) and SFJ (J-Ring)

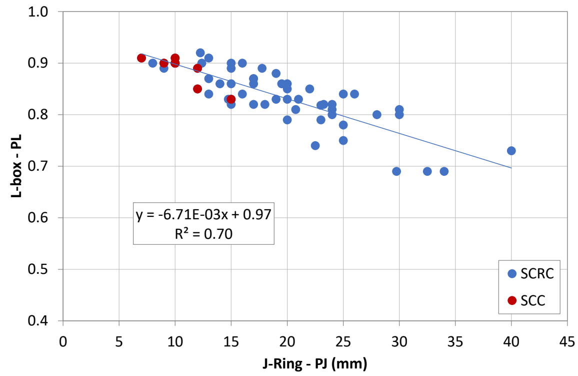


Figure VI-5. Relationship between PJ (J-Ring) and PL (L-box)

A quite good correlation between the L-box ratio and the SFJ value was identified (Figure VI-6). Similar comments to those of SF-PL relationship (Figure VI-2) can be made. The PL index is shown to increase with the SFJ parameter. A PL ≥ 0.8 (the minimum for self-compactability) is achieved if there is a high slump flow measured with the J-Ring test (SFJ ≥ 660 mm). In this way, all SCRC mixes with high SFJ values exhibited good passing ability measured with the L-box test.

In Figure VI-7 the PJ parameter decreases with the increase in SFJ value, in accordance with the SF-PJ relationship (Figure VI-3). Also, in this case, a good correlation between the SFJ and PJ values with a R^2 of 0.80 can be seen. The new established limit of PJ (PJ ≤ 25 mm) corresponds with SFJ values greater than 650 mm, which is indicative of good filling capacity and of SF values (Figure VI-4) also greater than 650 mm.

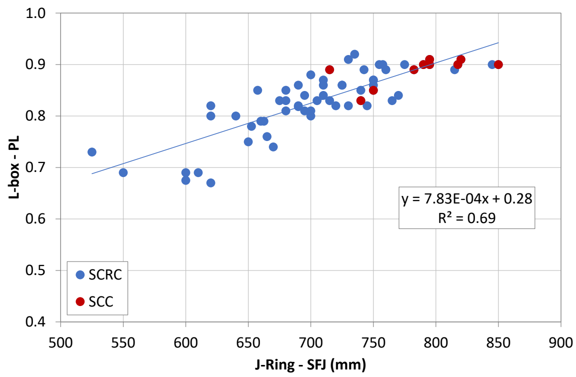


Figure VI-6. Relationship between SFJ (J-Ring) and PL (L-box)

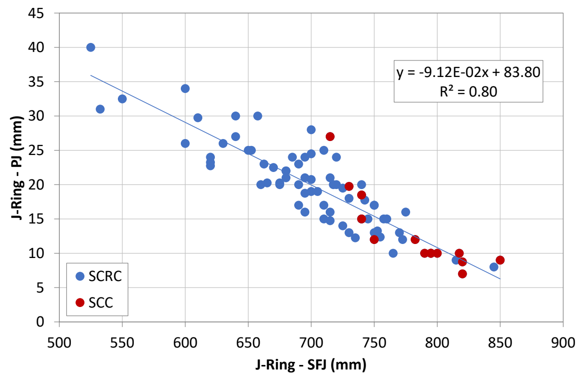


Figure VI-7. Relationship between SFJ (J-Ring) and PJ (J-Ring)

Lastly, Figure VI-8 shows a quite good relationship between the t500 and t500J times of slump flow and J-Ring tests respectively, with a R^2 coefficient of 0.75. From the derived correlation (Figure VI-8), the range of [2-5] s established for the t500J parameter in Chapter V can be now verified taking into account the t500 range of [0.8-3.8] s [TEST04].

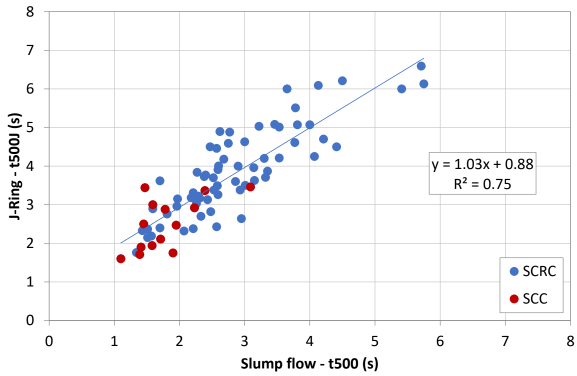


Figure VI-8. Relationship between t500 (slump flow) and t500J (J-Ring)

2.2 Relationships between empirical and rheological parameters

According to different literature works [TEST04, ROUS06c], the relationship between the static yield stress and the slump flow value (SF) and PL ratio (PL) at 15 min were obtained (Figure VI-9 and Figure VI-10).

In Figure VI-9, a similar relationship between the slump flow diameter (SF) and yield stress to the one proposed in conventional SCC [ROUS05] was analysed for SCRC. In Figure VI-10, linear regression was used to correlate the static yield stress and the L-box parameter (PL). In the first case, the adjustment was evaluated with the Pearson correlation coefficient (*r*). In the second case, when linear regression was used, the square of this coefficient (also called coefficient of determination, R^2) can be employed. Both coefficients show that the correlations are good and that the usual tendency obtained in SCC is also observed in SCRC.

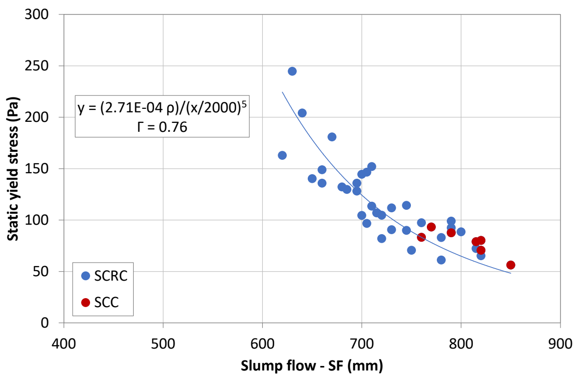


Figure VI-9. Relationship between slump flow (SF) and yield stress (ρ: fresh density (kg/m^3))

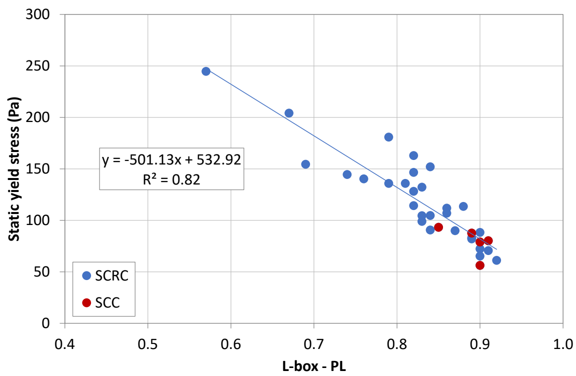


Figure VI-10. Relationship between L-box (PL) and yield stress

Lastly, two good relationships for plastic viscosity with t500 (slump flow test) and with t500J (J-Ring test) were obtained (Figure VI-11 and Figure VI-12, respectively). Also in this case, the tendency obtained in SCC is in agreement with that observed in SCRC.

In conclusion, it can be stated that the same relationships between empirical parameters and between empirical parameters and rheological properties can be used for conventional and recycled self-compacting concretes. The same tendency was observed in SCC as well as in SCRC regarding all relationships.

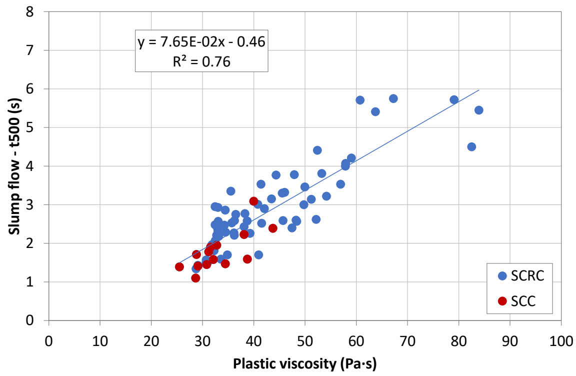


Figure VI-11. Relationship between slump flow (t500) and plastic viscosity

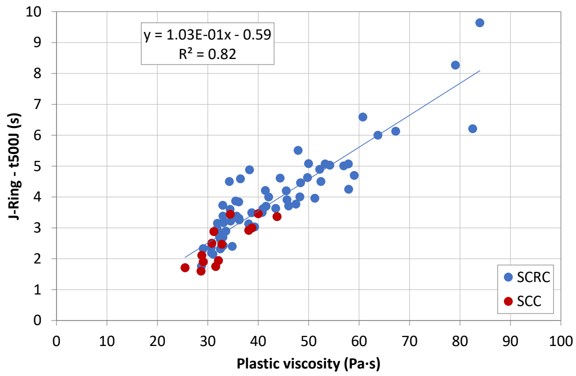


Figure VI-12. Relationship between J-Ring (t500J) and plastic viscosity

On the other hand, according to all the obtained relationships, all the limits established to empirical parameters in SCC are suitable for SCRC. Only the PJ parameter seems to be too strict to analyse the blocking behaviour in SCRC, as it was also concluded when SCC was studied [TEST04]. In this study, a maximum value of PJ level of 25 mm was determined. With this value, the SF and SFJ values ≥ 660 mm and a limit of PL ≥ 0.8 are guaranteed. Moreover, a direct correlation between both SF and SFJ parameters was observed. This means that SCRC mixes with high filling ability (high slump flow values) show a high filling capacity (filling ability plus passing ability) measured with the SFJ parameter of the J-Ring test.

Lastly, it has been seen that it is difficult to separate filling ability, passing ability and segregation resistance. Each of them is affected by the others. Inadequate passing ability can be due or aggravated by poor filling ability or poor segregation resistance. Blocking can also occur due to the mix design itself. Therefore, according to all the obtained results and in agreement with other authors [TEST04], none of the empirical tests was found to adequately cover all key characteristics of SCRC as a single test, moreover, there is no combination of tests that has been able to achieve this universal approval.

2.3 Use of a workability box to define suitable SCRC fresh behaviour

Due to the difficulties aforementioned (none of the empirical tests cover all fresh SCC characteristics, and there is no agreement regarding the best combination of them) different approaches to facilitate the design of a SCC of a particular application have been developed. One of them are the workability boxes. A workability box consists of a certain domain of yield stress and plastic viscosity associated with a particular concrete type and related to a job application. It should be clear that a workability box does not have to consist of a perfect square. It can also consist of a two-dimensional polygon, or pointed regions without an exact and clear boundary.

In this way, a workability box that guarantees a good rheological behaviour in the SCRCs used in this work (designed with an effective w/c ratio between 0.44 and 0.47, designed with recycled concrete coarse aggregate and designed compensating the water absorption) can be defined. In this sense, this area would avoid carrying out all the empirical tests, characterising the SCRCs with the two fundamental parameters of yield stress and plastic viscosity, developing only rheological tests.

The criterion to build this two-dimensional polygon was to fulfil some combination of different empirical parameters, taking into account their relationship with the main SCC fresh properties: segregation resistance, filling ability, passing ability and filling capacity (combination of the others).

According to the literature and to previous results, the empirical tests recommended for standardisation are related to these properties as follows [TEST04]:

- Sieve segregation test: mainly to assess segregation resistance.
- Slump flow test: SF and t500 parameters, mainly to assess filling ability. Visually to observe tendency to segregation.
- L-box test: PL parameter, mainly to assess passing ability.
- J-Ring test: PJ parameter, mainly to assess passing ability, and SFJ parameter, related to filling capacity (a combination of passing ability and filling ability, as a passing ability test can be used in conjunction with a filling ability test to evaluate the level of filling capacity [HWAN06]).

Therefore, two workability regions were obtained relating the parameter of passing ability to the parameter of filling ability, that is, PL to t500 (Figure VI-13) and SF to t500J (Figure VI-14). In these regions, the SFJ parameter was also considered and those mixes that did not pass the sieve segregation test (with SR ≥ 20%) were previously discarded.

Figure VI-13 identifies a workability region (WR1) where SCRC can develop both filling and passing abilities corresponding to a t500 time between 0.8 and 3.8 s and a PL parameter higher than 0.8. Moreover, this workability region is also defined by the result of the J-Ring flow (SFJ between 610 - 850 mm).

In Figure VI-14, the workability region (WR2) corresponds to mixes with a slump flow value (SF) between 660 and 850 mm and a t500J time of J-Ring test between 2 and 5 s. Again, regarding the J-Ring flow (SFJ), this workability region is defined considering the same aforementioned limits.

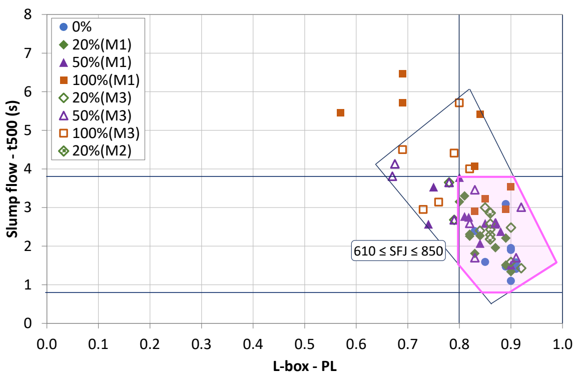


Figure VI-13. Workability region 1 (WR1): t500, PL, SFJ

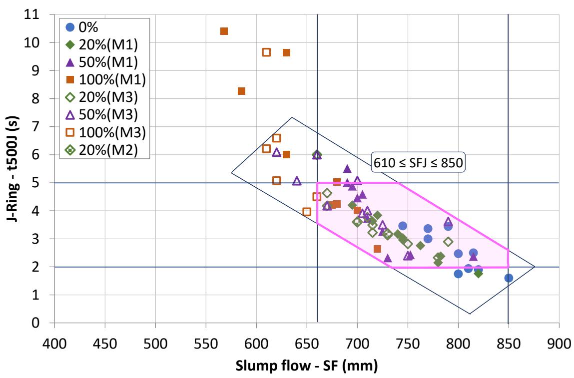


Figure VI-14. Workability region 2 (WR2): t500J, SF, SFJ

Lastly, each mix was classified and coloured regarding the number of workability regions that it fulfilled (two, one or zero). Then, the mixes that fulfilled the two workability regions were grouped in an area defined by a polygon that can be really considered as a workability box (WB15) (Figure VI-15). This workability box shows recommended combinations of both static yield stress and plastic viscosity for the SCRCs at 15 min. Moreover, a second box (WB45) (Figure VI-15) defines the time-dependent evolution of these rheological values until 45 min. In both of these areas, the designed SCRCs satisfy the following limits:

- 660 mm ≤ SF ≤ 850 mm
- 0.8 s ≤ t500 ≤ 3.8 s
- 0.8 ≤ PL ≤ 1
- 610 mm ≤ SFJ ≤ 850 mm
- SR ≤ 20 %

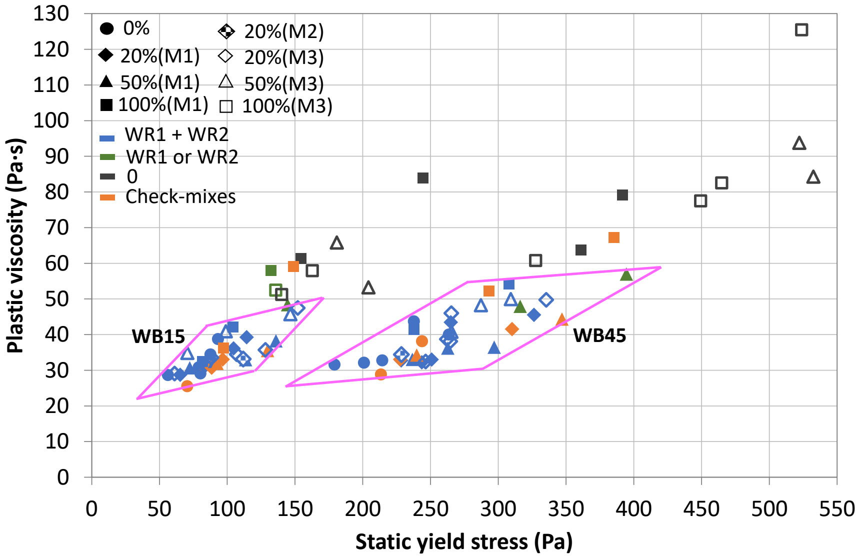


Figure VI-15. Workability box for SCRC

Furthermore, in Figure VI-15, the orange points were used to check the proposed workability box. These points correspond to mixes made with the cement variations. As it can be seen, the orange points that lie inside the WB15 evolve to the orange points within the WB45. Moreover, it has been checked that those points correspond to SCRC mixes with no segregation index and that they satisfy the limits defined by the two workability regions (WR1 and WR2), which are 660 ≤ SF ≤ 850 mm, 0.8 ≤ t500 ≤ 3.8 s, 0.8 ≤ PL ≤ 1 and 610 ≤ SFJ ≤ 850 mm.

3 RHEOLOGICAL BEHAVIOUR OF SCRC AT 15 MIN

It is well accepted that empirical tests are very often operator-sensitive, in the sense of minor variations in the execution of the test lead to different results. Moreover, the literature points out the necessity of describing the rheological behaviour of fresh concrete in terms of fundamental physical magnitudes, avoiding the dependence on the apparatus details or the operator [WALL11]. In this sense, some authors suggest the use of rheograhs to further understand concrete workability and rheology.

A rheograph is a plastic viscosity – yield stress diagram established in order to reveal in a systematic way the effects of diverse changes in the constituents on the rheological behaviour of the cement-based suspension (e.g. concrete, mortar and cement paste).

Therefore, in this section, a rheograph relating static yield stress and plastic viscosity is plotted to evaluate the influence of the incorporation of recycled concrete coarse aggregate on the rheological behaviour of SCRC. Results obtained at 15 min with baseline mixes and water variations, both carried out with the M1 method, are used to develop this analysis.

Lastly, the influence of different material variations on the rheological behaviour of SCRC are studied developing rheographs with the other "Robustness" mixes carried out with the M1 method and collecting results at 15 min.

3.1 Influence of % RCA

Water is well accepted to be one of the most important parameters affecting rheology. Moreover, the main recycled aggregate characteristic is its high absorption capacity that modifies the effective water to cement ratio of recycled concrete, $(w/c)_{ef}$. In this way, the mixes with water variations added to the baseline mixes offer a suitable range to study the foundations of SCRC rheological behaviour.

The increase in the recycled coarse aggregate content (% RCA) results in an increase in rheological values, i.e. both static yield stress and plastic viscosity. At 15 min (Figure VI-16, Figure VI-17 and Figure VI-18), as the replacement percentage increases, the yield stress and the plastic viscosity also increase, especially for the highest replacement ratio (100% RCA). Moreover, in general, it can be seen that the influence of recycled coarse aggregate is shown to be quite similar on both rheological parameters. Even so, the incorporation of recycled coarse aggregate of up to 50% affects the static yield stress slightly more than the plastic viscosity. In the case of 100% RCA, both properties are affected to the same extent compared with those of conventional SCC (SCRC0).

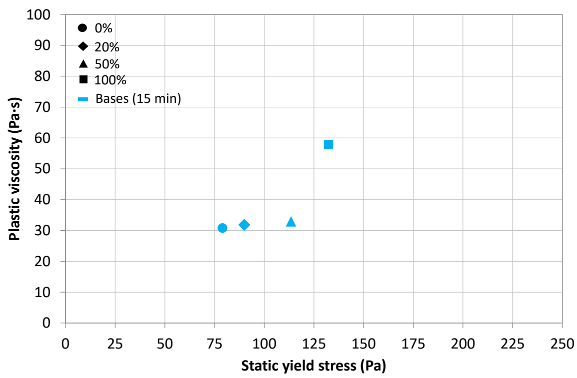


Figure VI-16. Static yield stress vs. Plastic viscosity (baseline mixes)

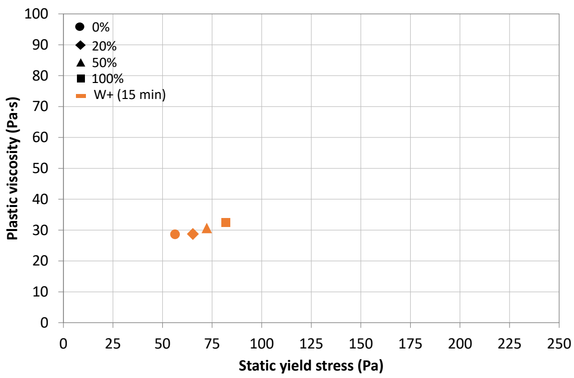


Figure VI-17. Static yield stress vs. Plastic viscosity (water increase)

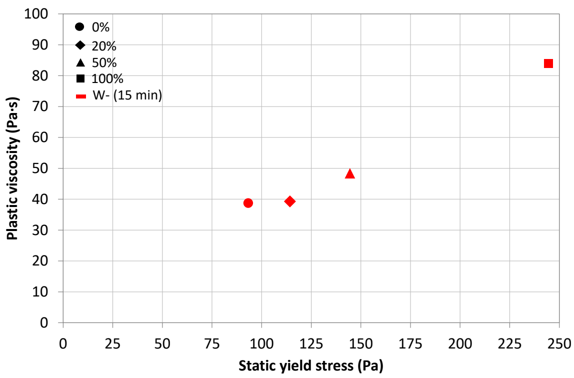


Figure VI-18. Static yield stress vs. Plastic viscosity (water decrease)

The incorporation of recycled aggregate may imply some changes that can justify the increased values of the concrete rheological properties. These changes can be summarized as follows:

- The w/c ratio increases because of the evolution of water absorption of the recycled aggregate.
- The morphological characteristics of this type of aggregate are different from those of the conventional aggregate in different aspects: shape, texture, fines content, and packing density.

Regarding the first change, it is well known that the **w/c ratio** influences rheological properties, plastic viscosity and yield stress [BANF06, HU05]. Both increase as the w/c ratio decreases. The evolution of non-compensated water absorption of recycled aggregate implies that the effective w/c ratio at 15 min is different between conventional and recycled concretes. Therefore, the evolution of the w/c ratio due to the evolution of the water absorption of the recycled aggregate has to be considered in the rheological SCRC analysis.

Regarding the second change, according to several authors [AISS16, KOEH04, QUIR03], it is necessary to consider the morphological characteristics of aggregates in order to understand the concrete workability and rheology. Therefore, the comparison of the properties of recycled coarse aggregate (shape, texture or roughness, fines content, packing density and flat and elongated particles) with those of conventional aggregate need to be considered.

The shape of a rock particle is suggested to be expressed in terms of “overall shape” and roundness (large scale smoothness), although surface texture (fine scale smoothness) also has to be considered. These are geometrically independent although there may be a natural correlation between them in the sense that a process that affects one may promote or inhibit the development of others. One of the older definitions of aggregate particle shape is a qualitative one based on morphological observations. While older definitions are often qualitative, more recent definitions are quantitative [ERDO05].

Therefore, in general, **shape** is measured with the terms of “overall shape” and roundness. “Overall shape” is related to two different characteristics: sphercity and form. Sphericity is a measure of how nearly equal the three principal axes or dimensions of a particle are. Form is the measure of the relationship between the three dimensions of a particle based on ratios between the proportions of the long, medium, and short axes of the particle. Form, also called “shape factor,” is used to distinguish between particles that have the same numerical sphericity. Regarding sphericity and form, particles can be classified qualitatively as cubical, spherical, or flat and elongated [QUIR03]. Finally, roundness attempts to describe the outline of the particle, which may be measured in terms of “convexity”. It is associated with the angularity, which is related to the sharpness of the edges and corners of a particle.

Regarding **texture**, surface texture is a measure of the roughness of the particle boundary and is independent of the “overall shape” and roundness.

Concerning the recycled coarse aggregate used in this work, it was observed (Chapter III) that its shape is very similar to that of the natural coarse one. Both are crushed aggregates, and they can be defined as aggregates with a high sphericity. The natural coarse aggregate may be considered as a sub-angular aggregate (evidence of some wear, but faces untouched) and the recycled one as an angular aggregate (little evidence of wear on the particle surface).

However, the recycled coarse aggregate is more porous and rougher than the natural one due to the adhered mortar (it has a different texture). It is known that this property influences the concrete’s fresh behaviour, aggregates with spherical, cubical, or rounded shapes and smooth textures require less cement and water to achieve the same slump as aggregates with flat, elongated, or angular shapes and rough textures [QUIR03]. Therefore, this property has to be considered in the SCRC rheological analysis.

The **fine particles** are typically considered as those with apparent diameters less than 80 µm. The amount of fines should be considered as powder material in proportioning SCC. Such fine content can have a marked effect on SCC rheology [KHAY08]. These fines include cement, supplementary cementitious materials, mineral fillers, fines in the aggregate and dust-of-fracture aggregate microfines. There is no agreement about a discrete size for distinguishing solid materials that should be included in the paste. Some of the studies consider fine particles as those with an apparent diameters of less than 0.125 mm [KHAY08] whereas others consider that 75 µm is a reasonable and practical value [KOEH07, MIRA06]. However, recent studies observed that coarser fines, ranging between 80 and 315 µm, have a considerable influence on concrete workability [AISS16].

Regarding fines in aggregates, the quantity that might be desirable, tolerable or deleterious depends upon the properties of these microfines and the type of concrete that will be made. The parental rock and the crushing method affect the shape, texture and grading of the resulting aggregate, as well as the amount and geometric characteristics of microfines [QUIR03]. Then, the shape and surface texture of fine particles have a significant impact on concrete and mortar rheology, observable in water demand, depending on the type of aggregate used. More volume of paste is needed to reduce the inter-particle friction attributable to the larger number of contact points resulting from the irregular shape and rougher texture of the grains of crushed fine particles compared to regular shapes and smooth textures [CABR11].

Due to the nature of the recycled aggregate, in general, high microfines content (rough and not rounded particles) and high sand content are going to be included in the recycled coarse aggregate grading [SAFI11, SILV16]. This higher content of fine particles increases the total surface area of the recycled aggregates [LIMA14] and this, along with its shape and texture, contribute to decrease the effective w/c ratio. In fact, it is well known that the use of recycled fine fractions largely affects the fluidity of recycled concretes [JUAN04]. In this work, when the particle size distribution was obtained (Chapter III, Figure III-9), it was observed that the content of sand and fines in the recycled coarse aggregate was higher than that of the natural coarse one.

On the other hand, there are studies that have found a loss of workability of recycled concretes due to the generation of fines from the wear of old adhered mortar during mixing [SAFI11]. Thus, recycled aggregates from parent concretes of low strength produce more fines than those from wear of adhered mortar and more loss of workability [JUAN04, HANS83].

Moreover, some of these fines can show hydration capacity, decreasing the expected effective w/c ratio after measuring the water absorption over time of the recycled aggregate, also changing the mortar composition of concrete. Thus, the surface is likely to be worn by impact or friction between aggregates, and unhydrated cement particles could be exposed on the surface, which means the old cement on the surface of the recycled aggregate could be hardened due to a reaction with water. When the old cement mortar reacts with water, it is possible for the old cement on the surface of the aggregate to increase the unit cement volume [DONG12].

Since the hydration reaction thickness of cement is about 25 µm, there might be an interior core of unhydrated cement even though the cement appears as if it has already been hydrated. When recycled aggregate is produced, it leaves a lot of fine particles on the surface due to some wear of cement caused by abrasion in the course of production or impact, causing the unhydrated cement to expose externally. The unhydrated cement particles attached to the recycled aggregate could initiate a hydration reaction, which could have an influence on the workability of concrete [SAID14, DONG12].

To sum up, the fines content of recycled coarse aggregate used in this work can increase the water demand mainly due to its high absorption, its irregular shape and its rough texture. Moreover, the adhered mortar of the recycled coarse aggregate can break during mixing, providing fines that can react with water and be hydrated, changing the mortar composition of the studied concrete. Hence, the fine particles have to be considered when analysing rheology of SCRC.

Lastly, with the development of concrete rheology studies, it was found that it is not only determined by the volume fraction of aggregate, but it is also related to the type of aggregate. Introducing a new parameter named **maximum packing fraction** of aggregate ($\varnothing_{max}$), some equations were obtained to predict concrete viscosity based on the volume concentration of aggregate (for example, the Krieger-Dougherty equation). The maximum packing fraction is defined as the solid volume concentration at which the particle concentration results in three-dimensional contact throughout suspension and the viscosity approaches infinity [KOEH04].

The $\emptyset_{max}$ parameter was found to be in the range of 0.64-0.80 depending on several characteristics of the aggregate, including particle-size distribution, shape and sand-to-total aggregate volume ratio. In general, mixes made with rounded aggregates (regular shape) have greater packing density than those prepared with crushed aggregates (irregular shape). In addition, aggregates with smooth texture also contribute to increase the packing density compared with aggregates with rough texture.

Therefore, although both recycled and natural coarse aggregates that are used are crushed aggregates, it is expected that the higher roughness of the former leads to a worse packing density. However, the slightly better shape and the greater presence of fines in the recycled aggregate imply a packing density (and therefore a maximum packing fraction) similar to that of a natural aggregate or even slightly higher in the recycled aggregate than in the natural aggregate, as seen in Chapter III (Figure III-13).

Hence, to analyse the differences found between the rheological properties of self-compacting recycled concrete and those of conventional self-compacting concrete (Figure VI-16), it will be necessary to take into account the influence of all described parameters on viscosity and yield stress.

In the literature [KOEH07], it is indicated that self-compacting concrete rheology must be optimized from paste and mortar phases to concrete phase. In fact, most authors [ROUS10] consider that concrete is a material composed of a viscous liquid with solid particles in suspension that at a macroscopic scale can flow as a liquid.

Then, different equations have been developed to study concrete rheology. One of the equations that has been used and that provides satisfactory results, although requiring the use of the maximum packing fraction, $\emptyset_{max}$, is the Krieger-Dougherty equation which considers that the **viscosity** of a suspension can be calculated as follows:

$$\mu = \mu_s \cdot \left(1 - \frac{\emptyset}{\emptyset_{max}}\right)^{-[\mu]\cdot\emptyset_{max}} \qquad (1)$$

Where:

μ is the viscosity of the suspension (solid phase and solvent)

μ_s is the viscosity of the solvent

$[\mu]$ is referred to as the intrinsic viscosity of the solid phase

$\emptyset_{max}$ is the maximum packing fraction

$\emptyset$ is the solid volume concentration

A particular difficulty with the Krieger-Dougherty equation is the distinction between the solid and the solvent and the definition of their respective properties. Authors agree with the fact that paste rheology is a function of water rheology, mortar rheology is a function of paste rheology and finally concrete rheology is a function of mortar rheology. In cement paste, the solvent is obviously water, whereas in concrete the question is whether it is the water, the cement-water paste, or the cement-water-fine aggregate (mortar), because these three cases exhibit very different values of solid volume fraction and relative viscosity [BANF06].

In this work, according to different authors [KOEH07], the cement paste can be considered itself as a suspension of solid materials finer than approximately 75 µm including cement and cementitious materials in water. The mortar can be considered as the suspension of fine aggregates (solid phase) in cement paste (solvent), and finally, in concrete the mortar acts as the solvent that contains the coarse aggregates.

Regarding **yield stress**, based on an analogy with the Krieger-Dougherty equation (suitable for concentrated suspensions), the yield stress of concrete can be considered proportional to the yield stress of mortar [MAHA08, YAMM08] and this, in return, to the yield stress of paste. Then, they are amplified by the aggregates used, once again, throughout the relation "solid volume fraction - maximum packing fraction" [TOUT06].

That is:

$$\tau_{0,m} \propto \tau_{0,p} \tag{2}$$

$$\tau_{0,c} = \tau_{0,p} \cdot f\left(\frac{\emptyset}{\emptyset_{max}}\right) \tag{3}$$

Then:

$$\tau_{0,c} \propto \tau_{0,m} \cdot f\left(\frac{\emptyset}{\emptyset_{max}}\right) \tag{4}$$

Being:

$\tau_{0,c}$ is the yield stress of concrete

$\tau_{0,p}$ is the yield stress of the paste

$\tau_{0,m}$ is the yield stress of the mortar

$\emptyset$ is the solid volume fraction

$\emptyset_{max}$ is the maximum packing fraction

Therefore, the effect of aggregates on concrete rheological properties can be studied considering concrete as a suspension of coarse particles in the mortar, and this seen as a continuum medium, as a suspension of aggregates in paste.

Taking this into consideration, concrete viscosity depends on the viscosity of the solvent (that can be considered as the mortar), on the intrinsic viscosity of aggregates (that depends on their shape, texture and grading), and on the "solid volume fraction - maximum packing fraction" function (that depends on the concrete composition and on the shape, texture and grading of aggregates). All of these parameters will be analysed using the aforementioned equations to understand the influence of recycled aggregate on the SCRC rheological behaviour.

3.1.1 Regarding the solid phase

As presented, volume fraction models were used to predict the rheology of cementitious materials by relating aggregate volume percentage (volume fraction) to concrete rheology. The basic idea of this kind of model is that the viscosity of a composite increases with increasing volume of solids.

A lot of models [BANF06] based on the idea of volume fraction have been developed to describe the rheological parameters of composites including cementitious materials, most of which analyse fresh concrete as a paste/aggregate composite. These models generally attempt to infer the viscosity of the concrete from the paste viscosity by multiplying it by a function that takes the volume of granular phase into consideration.

Results from Geiker et al. [GEIK02] showed that the relative yield stress and relative viscosity, which were defined as the rheological parameters of concrete divided by the parameters of mortar, both increased significantly with the increase of coarse aggregate volume fraction, no matter what type of aggregate was used.

Moreover, not only volume fraction but also shape of aggregate particles can also affect rheology. Generally, the more nearly spherical the particles, the more workable the resulting concrete will be. The gradation and the fine-to-coarse aggregate ratio will also affect concrete rheology. These characteristics can be considered with maximum packing fraction.

Therefore, as mentioned, the solid-volume-fraction/maximum-packing-fraction ($\O/\O_{max}$) ratio is an important parameter that affects rheology. Many researchers [FERR01, HU05, TOUT06] report the variation of plastic viscosity and yield stress with $\O/\O_{max}$ ratio, showing the typical exponential form for the relationship. As the $\O/\O_{max}$ ratio increases, the concrete mix decreases its plastic viscosity and its yield stress (Figure VI-19).

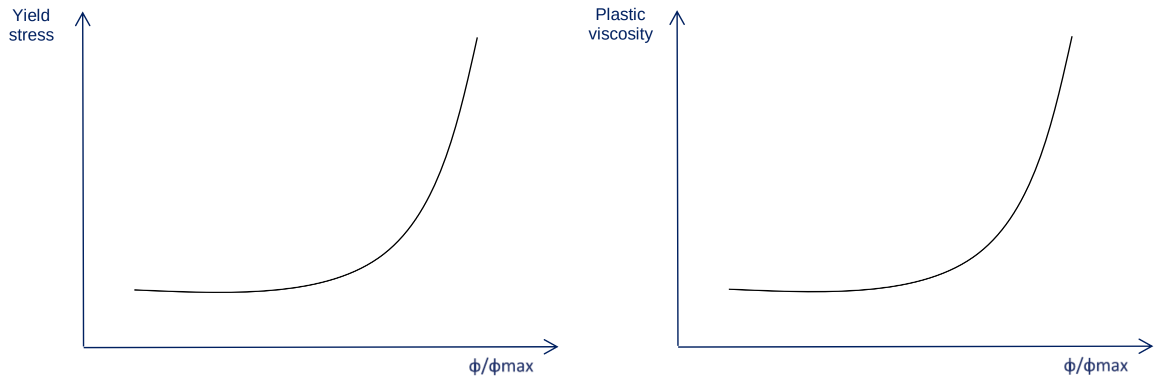


Figure VI-19. Yield stress and plastic viscosity vs. $\O/\O_{max}$ ratio

The $\O/\O_{max}$ ratio is calculated with the maximum packing fraction ($\O_{max}$) that depends on particle size, shape, texture and fines content of the aggregate skeleton. As aforementioned, the recycled coarse aggregate used in this work has a slightly better shape, worse texture and higher fines content than the natural one. Due to the sum of these characteristics, the $\O_{max}$ of the aggregate skeleton of SCRCs presents a slight tendency for increasing as the replacement percentage increases, Figure III-13 (maximum packing fraction of different granular skeletons) of Chapter III.

However, rheological properties do not only depend on the solid-volume-fraction/maximum-packing-fraction ($\O/\O_{max}$), but also on the aspect ratio of the particulate phase. Therefore, the aspect ratio needs to be considered taking into account detailed information on particle shape and texture [GEIK02]. In the exponent $[\mu]\cdot\O_{max}$, the intrinsic morphological characteristics of aggregates are collected (shape and texture). The intrinsic viscosity $[\mu]$ varies from 2.5 for spheres to higher values for asymmetric particles, in the range of 4.5-6.8 [BANF06].

Concrete is more workable when smooth and rounded aggregate is used instead of rough angular or elongated aggregate. Most natural sands and gravel from riverbeds or seashores are smooth and rounded and are excellent aggregates for proper workability. Crushed stone produces much more angular and elongated aggregates, which have a higher surface-to-volume ratio, better bond characteristics but require more cement paste to produce a workable mix.

The effect of varying degrees of surface texture on the rheological properties has not been ascertained and conflicting findings are available [ERDO08]. One problem with determining the effect of texture on flow properties is that it is difficult to separate the effect of two different length scale shape properties, like overall shape and surface texture. While natural aggregates tend to have more equal-dimensional and rounded shapes, and manufactured aggregates tend to have more elongated (and/or flat) and angular shapes, both types of aggregates may have smooth or rough surfaces.

In general, irregular shape and rough surface texture of the crushed aggregate is the main cause of several inter-particle forces and this, correspondingly, increases yield stress and plastic viscosity of concrete [AISS16]. Rough-textured aggregate tends to increase the water demand for a given workability. Surface texture affects particle-packing efficiency, and the impact of surface texture on concrete behaviour becomes more important as particles get smaller [QUIR03].

In Figure VI-20, two types of aggregate have been represented to explain the relationship between their characteristics (shape and texture) and rheological properties, yield stress and plastic viscosity. On the one hand, aggregate type 1 can represent a rounded aggregate and aggregate type 2, a crushed aggregate. On the other hand, aggregate type 1 can represent a crushed aggregate with smooth texture and aggregate type 2 with rough texture. These relationships can be found in the literature [GEIK02] indicating that yield stress and plastic viscosity can increase if the aggregates used show irregular shape and a rough texture.

As aforementioned, recycled aggregate presents a similar shape as natural aggregate (similar value of $\emptyset_{max}$) being, however, more porous and much rougher than the natural one due to the adhered cement paste (then, [µ]·will be higher). Therefore, in Figure VI-20, aggregate type 1 can be associated with the natural coarse aggregate used in this work and aggregate type 2 with the recycled one (Figure VI-21).

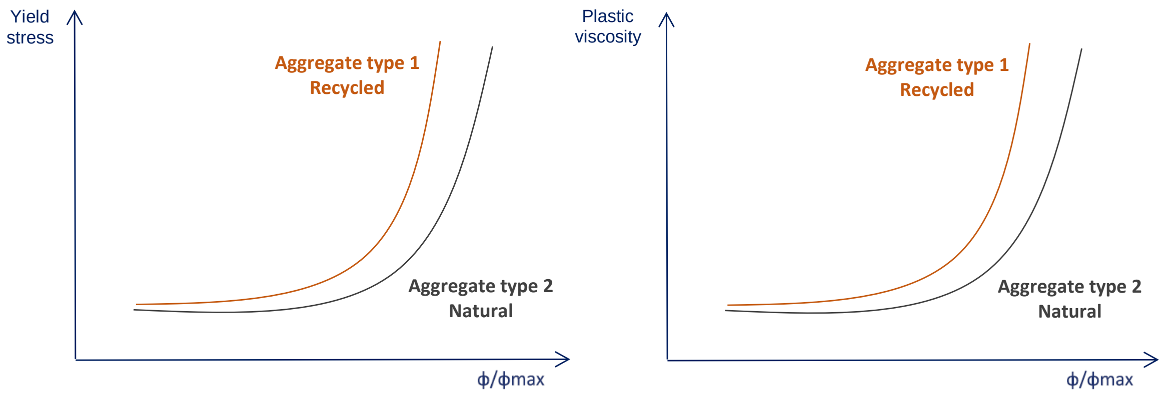


Figure VI-20. Rheological property vs. $\emptyset/\emptyset_{max}$. Type of aggregate

Figure VI-21. Natural (left) and recycled (right) coarse aggregates

3.1.2 Regarding the solvent

In the previous equations of viscosity and yield stress (Eq. 1 and 4), the w/c ratio is considered inside μ_S and $\tau_{0,m}$, respectively. This means that w/c ratio is influencing concrete rheology throughout solvent (mortar or paste) rheology.

It is well known that water content is one of the most important factors governing concrete rheology. Increasing the water content while keeping the proportions of the other constituents constant will decrease yield stress and plastic viscosity. However, an excess of water may lead to segregation and bleeding.

Some statistical analyses were performed to quantify the effect of the w/c ratio on concrete rheology. It was found that both yield stress and plastic viscosity exponentially decrease as w/c ratio increases [BANF06, DEEB13] (Figure VI-22).

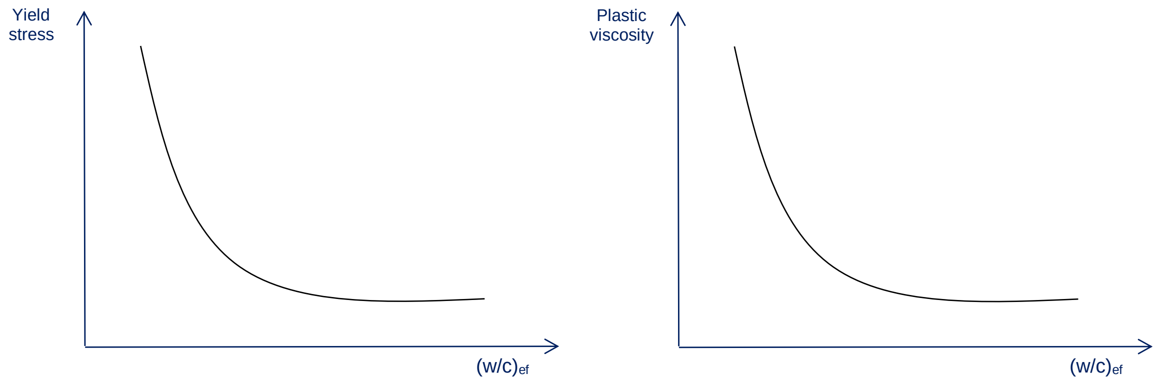


Figure VI-22. Yield stress and plastic viscosity vs. $(w/c)_{ef}$

In order to analyse the effect of the w/c ratio on SCRC rheology, different solvents (mortars of the SCRC mixes of this work) with different w/c ratios were designed (Chapter III). Their slump (mini slump flow) was measured since the correlation between yield stress and slump flow in pastes is already known and widely accepted. For high slump or high spread values, Roussel *et al.* [ROUS05] proposed a relationship that results in an accurate interpretation of the slump flow test in the case of pastes. This relationship considers that yield stress depends on the slump flow or spread raised to the power of minus five. Therefore, considering this, the following approximations can be made (Eq. 5-6):

$$\tau_{0,m} \propto \frac{1}{{SF_m}^5} \tag{5}$$

Being:

SF_m is the slump flow of the mortar (valued using mini slump flow test)

And according to Eq. 3:

$$\tau_{0,c} \propto \frac{1}{{SF_m}^5} \cdot f\left(\frac{\emptyset}{\emptyset_{max}}\right) \tag{6}$$

As aforementioned, the yield stress of the mortar is proportional to the yield stress of the paste and then proportional to the inverse of the slump flow raised to the power 5. The mini slump flow of the mortars was measured (as explained in Chapter III) and the yield stress increase of these mortars was computed taking into account a baseline mortar with a water to cement ratio of 0.5 (Eq. 7).

Finally, an exponential curve was adjusted using the multivariable regression technique to define the $\frac{\tau_{i,m}}{\tau_{ref,m}}$ ratio, named “yield stress variation” (Figure VI-23).

$$\frac{\tau_{i,m}}{\tau_{0.5,m}} = \left(\frac{SF_{0.5,m}}{SF_{i,m}}\right)^5 \quad (7)$$

$\tau_{0.5,m}$ is the yield stress of the mortar with a w/c ratio of 0.5

$\tau_{i,m}$ is the yield stress of the mortar with a given w/c ratio

$SF_{0.5,m}$ is the mini slump flow of the mortar with a w/c ratio of 0.5

$SF_{i,m}$ is the mini slump flow of the mortar with a given w/c ratio

The yield stress variations of these mortars as a function of the w/c ratios are plotted in Figure VI-23 showing an exponential relation. Therefore, high w/c ratios will not imply significant changes in yield stress, whereas low ones will lead to important ones, as seen by other authors [BANF06, DOMO88, DEEB13]. Then, Figure VI-23 can be used to predict yield stress variations in recycled concretes, SCRCs, caused by changes in w/c ratio.

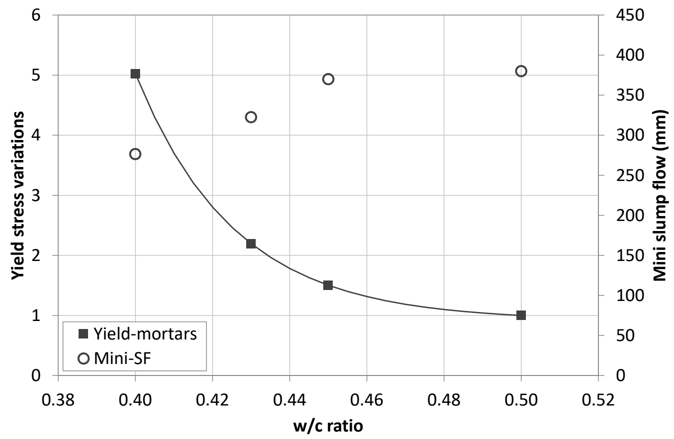


Figure VI-23. Yield stress variations vs. w/c ratio (mortars)

Therefore, the actual variations in static yield stress and plastic viscosity obtained with SCRCs are calculated. These variations are represented in Figure VI-25 and Figure VI-26 respectively, as a function of the effective water to cement ratio (Figure VI-24) obtained taking into account the evolution of the non-compensated water absorption. They have been calculated taking as a reference the value obtained with the SCRC0W+ mix.

The exponential curve adjusted to predict the increase of yield stress as a function of changes in the w/c ratio with the designed mortars can be compared with the actual values obtained for all conventional and recycled concretes (Figure VI-25).

The SCRC0 mix results show a tendency similar to the one of the curve adjusted with the mortars, which means that the mortar tested represents accurately the solvent of the SCRC0 mix. However, as the replacement percentage increases, the yield stress variations are further from those of the reference concrete, concluding then, that the mortar tested does not represent accurately the solvent of the SCRCs (Figure VI-25). The same tendency can be seen when plastic viscosity is analysed, especially in the case of the 100% replacement concrete (Figure VI-26).

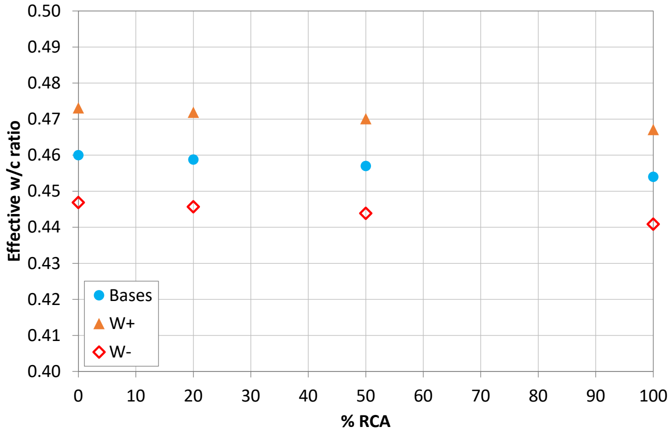


Figure VI-24. Water to cement ratio of SCRCs at 15 min

Therefore, as expected, changes in w/c ratio do not completely explain the variations detected in static yield stress and plastic viscosity of self-compacting recycled concretes. So, it can be concluded that other of the aforementioned factors are also influencing their rheological properties.

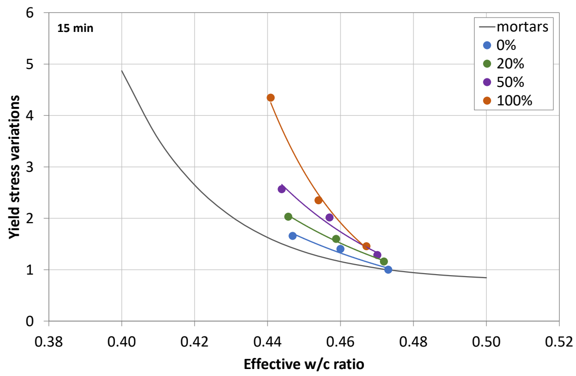


Figure VI-25. Yield stress variations vs. $(w/c)_{ef}$ regarding SCRC0W+

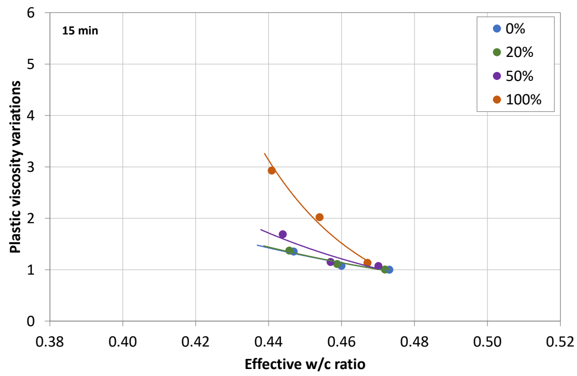


Figure VI-26. Plastic viscosity variations vs. $(w/c)_{ef}$ regarding SCRC0W+

To further understand the obtained curves, the yield stress and plastic viscosity variations are going to be evaluated analysing each series of self-compacting recycled concretes (SCRC0, SCRC20, SCRC50 and SCRC100) in an independent way (Figure VI-25 and Figure VI-26). To do so, the following equation (Eq. 8), which relates concrete rheological parameters with those of mortars, has to be considered:

$$\frac{(\mu_c)_{(w/c)_1}}{(\mu_c)_{(w/c)_2}} = \overbrace{\frac{(\mu_m)_{(w/c)_1}}{(\mu_m)_{(w/c)_2}}}^{\text{“Mortar factor”}} \cdot \overbrace{\left[\frac{1-(\frac{\emptyset}{\emptyset_{max}})_{(w/c)_1}}{1-(\frac{\emptyset}{\emptyset_{max}})_{(w/c)_2}}\right]^{-[\mu]\cdot\emptyset_{max}}}^{\text{“}\emptyset/\emptyset_{max}\text{, }[\mu]\text{, }\emptyset_{max}\text{ factor”}} \tag{8}$$

In this equation, the $\emptyset/\emptyset_{max}$ ratio is defined by the solid volume fraction ($\emptyset$). When SCRC is designed, this parameter changes at each measurement time due to water absorbed by the recycled coarse aggregate decreasing, obviously, the paste volume in concrete. In this work, the decreases in water detected in SCRC modify the $\emptyset$ value at 15 min, but they do not achieve to compensate for the slightly higher $Ø_{max}$ value of the SCRC granular skeleton. Therefore, slightly lower $Ø/Ø_{max}$ ratios are obtained in SCRCs (Figure VI-27). Moreover, the value of "$Ø/Ø_{max}$" of a mix with a fixed w/c ratio is slightly different from the value obtained in this mix with a different w/c ratio (Figure VI-27). This makes the "$Ø/Ø_{max}$, [μ], $Ø_{max}$ factor" of Eq. 8 slightly different from 1.

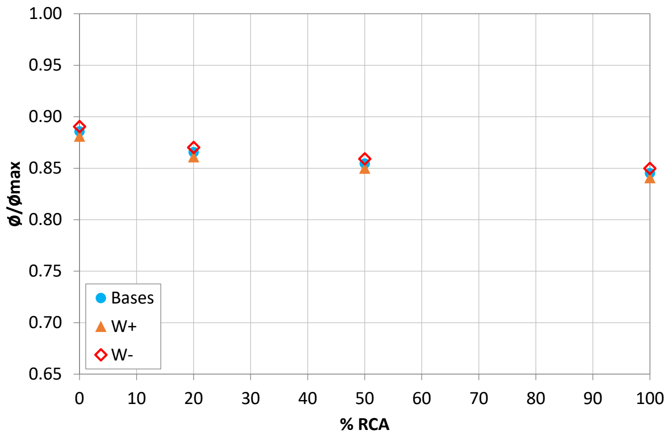


Figure VI-27. $Ø/Ø_{max}$ ratio of SCRCs at 15 min

Regarding the SCRC0 mix, the differences between mortar and concrete variations (Figure VI-25) are due to the variation in the "$Ø/Ø_{max}$" ratio produced when mixes with water changes are designed, as aforementioned. Therefore, viscosity variations will be slightly different from those obtained with a mortar analysis and, by analogy, the yield stress variations determined with concrete mixes are also different from those obtained with the tested mortars (although very similar).

However, although the variation in the "$Ø/Ø_{max}$" ratio produced in SCRCs mixes (SCRC20, SCRC50 and SCRC100) is similar to the one of the SCRC0 mix, the rheological variations obtained with these mixes are further from the ones predicted with the mortar analysis (Figure VI-25 and Figure VI-26). Moreover, the differences increase as the replacement percentage increases (SCRC100). According to previous discussion, this is due to the following two circumstances.

On the one hand, the rough-texture of recycled aggregate particles increases the harshness of the concrete mix, and thus decreases its workability and its rheological parameters, particularly at high replacement percentages. This fact is considered on the value of [μ], which is higher in recycled coarse aggregate than in the natural coarse one, as mentioned in section 3.1.1. As $Ø_{max}$ is similar in natural and recycled aggregates, then the value of "$[μ]·Ø_{max}$" is going to be higher in self-compacting recycled concretes. Therefore, the "mortar factor" is amplified by a "$Ø/Ø_{max}$, [μ], $Ø_{max}$ factor" that is higher in SCRCs (Eq. 8).

On the other hand, the highest content of fines in recycled aggregate leads to more quantity of fines in SCRCs. These fine particles show a very irregular shape and a very rough texture affecting negatively the SCRC rheology. Moreover, during mixing, more fines are generated due to the loss of the old adhered mortar and some of them can even present hydraulic activity. Both facts modify the characteristics of SCRCs solvent (mortar in concrete) and, therefore, the tested mortars are no longer representative of the mortar of SCRCs, especially in the case of the 100% replacement concrete (Figure VI-28).

$$\mu_c = \mu_m \cdot \left(1 - \frac{\emptyset}{\emptyset_{max}}\right)^{-[\mu]\cdot\emptyset_{max}}$$

$$\mu_m = \mu_p \cdot \underbrace{\left(1 - \frac{\emptyset}{\emptyset_{max}}\right)^{-[\mu]\cdot\emptyset_{max}}}$$

Water
Cement
Recycled fines with hydraulic activity

Sand + Fines of coarse aggregates
SCRC100 -> 17.61% (<4mm); 4.18% (<125 µm)
SCRC0 -> 11.14% (<4mm); 1.34% (<125 µm)

Figure VI-28. Explanation of SCRC rheological behaviour

Therefore, it is expected that the "rheological variations – $(w/c)_{ef}$" curves of a SCRC compared to a SCC are going to be different. For the same w/c variation, these curves predict higher rheological variations in SCRC, especially when the w/c ratio is low, due to the fact that changes are taking place in the high slope region of a high slope curve (Figure VI-29).

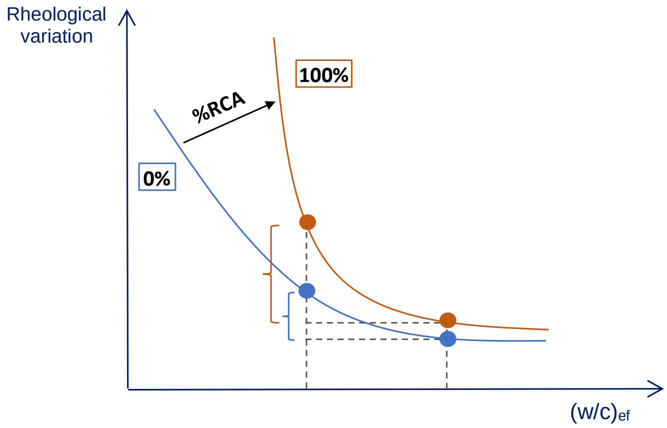


Figure VI-29. Rheological variations vs. Effective w/c ratio (SCC vs. SCRC)

3.2 Influence of materials variations

In this sub-section, the influence of different materials variations on SCRC rheological behaviour is analysed. For that, some rheographs collecting results at 15 min of mixes from "Rheology" and "Robustness" phases produced with M1 method are built.

Regarding superplasticiser variations, reducing superplasticiser marks a negative influence on rheological parameters of all SCRC mixes (independently of % RAC) to a similar extent (Figure VI-30).

Increasing superplasticiser implies to improve the rheological parameters (Figure VI-30). In this case, however, as the reference mix (SCRC0) was designed with a superplasticiser content near to the saturation point (Figure VI-31), the increase of superplasticiser did not affect in a great deal the mixes with a low replacement percentage. A high replacement ratio (especially 100% RCA), with a lower effective w/c ratio, noted this increase to a greater extent since its percentage of saturation of superplasticiser was further away from the designed one (Figure VI-32).

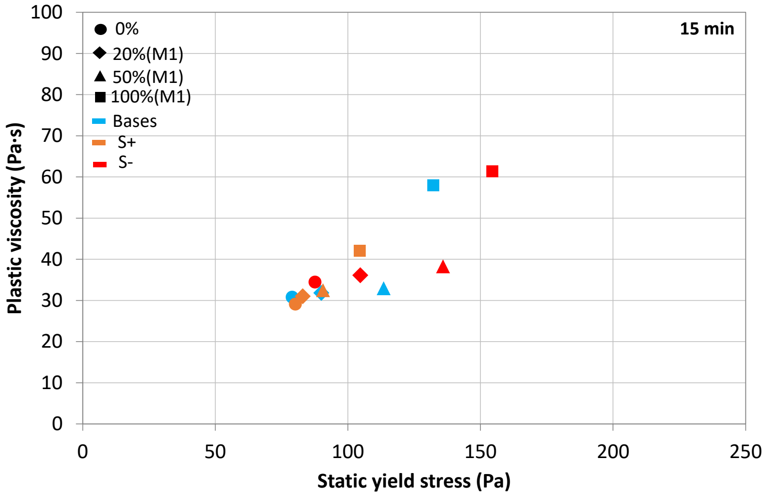


Figure VI-30. Static yield stress vs. Plastic viscosity. Superplasticiser variations

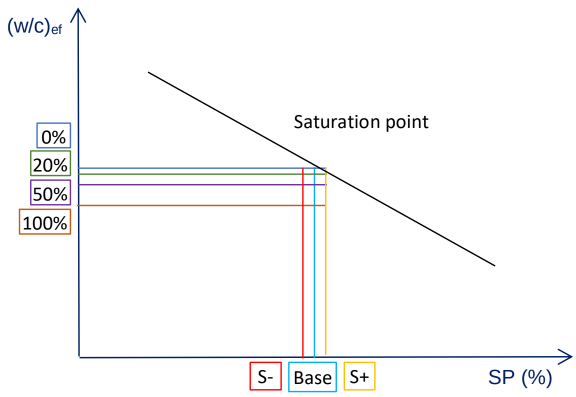


Figure VI-31. Effect of superplasticiser variations on saturation point of SCRCs

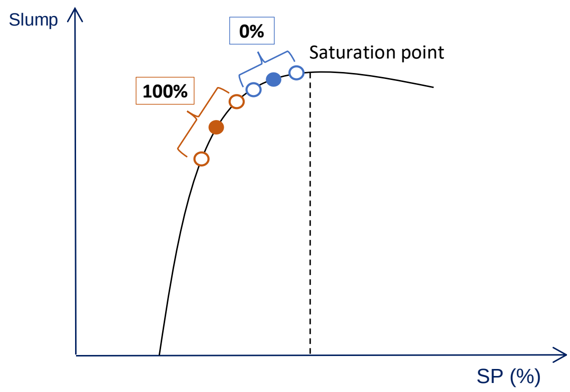


Figure VI-32. Slump vs. SP (%) (0-100% RCA)

Regarding cement variations (Figure VI-33), the increase of cement decreases the effective w/c ratio, decreases the superplasticiser/cement ratio but increases the paste volume. These changes lead to an increase in the rheological parameters of all concretes.

On the contrary, decreasing cement decreases the paste volume but increases the effective w/c ratio and increases the superplasticiser/cement ratio. In this case, these changes decrease the rheological parameters (Figure VI-33). For the cement variations, mixes with high replacement percentages experienced higher changes in the rheological parameters than mixes with low replacement ratios. This is due to the fact that, as aforementioned, these recycled mixes present a higher slope in the “rheological variations - $(w/c)_{ef}$” and “rheological property - $Ø/Ø_{max}$” curves than conventional ones.

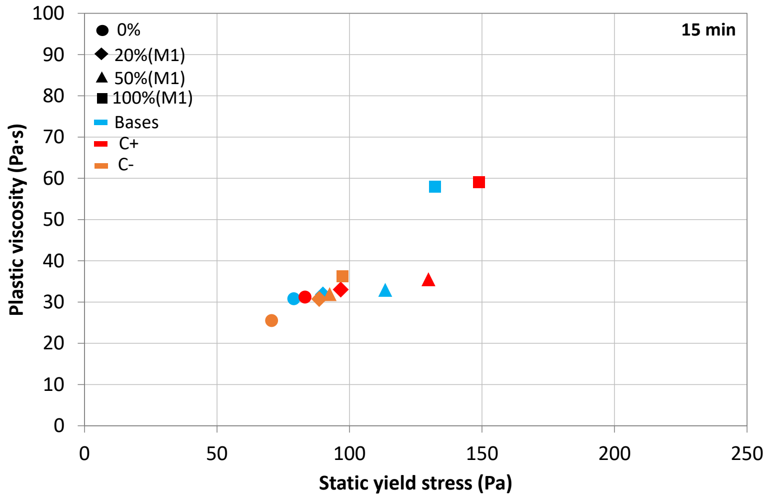


Figure VI-33. Static yield stress vs. Plastic viscosity. Cement variations

Regarding water variations, increasing water increases the effective w/c ratio. This fact decreases the values of yield stress and plastic viscosity (Figure VI-34). However, this decrease is more significant in 100% of RCA than in 0%, 20% and 50%. Decreasing water decreases the effective w/c ratio. Again, the rheological values vary more in recycled concretes than in conventional ones for the water changes since they present a high slope in the "rheological variation - $(w/c)_{ef}$" and "rheological property - $Ø/Ø_{max}$" curves.

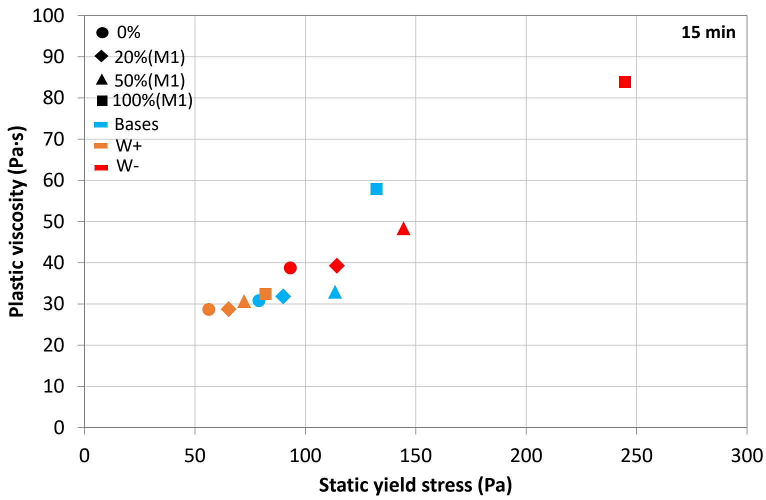


Figure VI-34. Static yield stress vs. Plastic viscosity. Water variations

Finally, comparing changes of different materials variations, when water decreases, $(w/c)_{ef}$ decreases and $Ø/Ø_{max}$ increases (there is less paste volume and the solid volume fraction increases). Both effects lead rheological values to decrease (Figure VI-35 and Figure VI-36). However, when cement increases, $(w/c)_{ef}$ decreases and $Ø/Ø_{max}$ decreases (there is more paste volume and the solid volume fraction decreases). Both effects counteract and finally rheological values decrease although to a lesser extent.

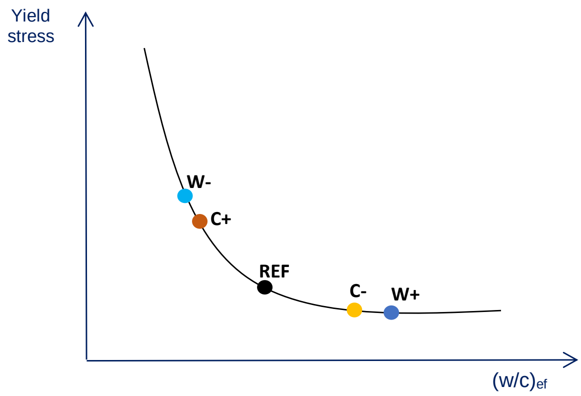


Figure VI-35. Yield stress vs. $(w/c)_{ef}$. Influence of materials variations

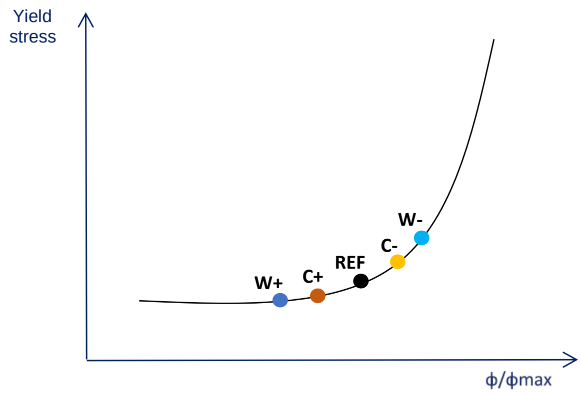


Figure VI-36. Yield stress vs. $Ø/Ø_{max}$. Influence of materials variations

On the other hand, when water increases, $(w/c)_{ef}$ increases and $Ø/Ø_{max}$ decreases (there is more paste volume and the solid volume fraction decreases). Again, both effects are additive (Figure VI-35 and Figure VI-36) leading rheological values to increase. However, when cement decreases, $(w/c)_{ef}$ increases and $Ø/Ø_{max}$ increases (there is less paste volume and the solid volume fraction increases). Again, both effects counteract and, again, rheological values increase to a lesser extent.

Moreover, changes in cement imply volumetric quantities lower than changes in water. Hence, the rheological variations regarding the reference mix will be lower when cement is affected than when water changes. Therefore, the sensitivity of a SCRC will be lower to cement changes than to water changes (Figure VI-35).

Finally, superplasticiser variations do not imply many significant volumetric changes. However, the effect of a superplasticiser also has to be evaluated taking into account its chemical activity. In this work, the sensitivity of SCRC to variations in this material was similar to that obtained with cement variations.

4 RHEOLOGICAL BEHAVIOUR OF SCRC OVER TIME

4.1 Introduction

The analysis made in the previous section showed that the specificity of the SCRC design lies in the quantity of extra water necessary to compensate the recycled aggregate absorption during the mixing protocol, which affects the effective water to cement ratio, and in the intrinsic characteristics of recycled coarse aggregate (shape, texture and fines content). In this work, mainly the rough texture (since both natural and recycled coarse aggregates are crushed-shaped) and the fines content in the recycled aggregate and generated during mixing by the wear of old adhered mortar change the baseline mortar leading to a different rheological behaviour of SCRCs (Figure VI-29). All these singularities lead to different “rheological variations – $(w/c)_{ef}$” and “rheological property – $Ø/Ø_{max}$” curves in a SCRC compared to a SCC.

Moreover, when the analysis is made over time, SCRC paste composition can be modified due to the time-dependent evolution of recycled aggregate water absorption, and water migrating to aggregate and diminishing the w/c ratio in the paste. Thus, it can be considered that recycled concrete presents a different effective w/c ratio as a function of the time elapsed, understanding the effective w/c ratio as that obtained after discounting the water absorbed by the recycled aggregate at each considered time.

So, the following step is to analyse the rheological behaviour of SCRC over time. For that purpose, the time-dependent evolution of slump flow and yield stress was studied. The first property evaluates the intrinsic yield stress of concrete and the second one, measured by a rheometer after the material being to rest, evaluates the static yield stress. Therefore, the difference between static and dynamic yield stress informs us on concrete thixotropic behaviour.

The structural characterization of time-dependent variations of SCC flow phase (thixotropy) is of utmost importance. Thixotropy is defined as a time-dependent process where a material is subject to "the continuous decrease of apparent viscosity with time under shear and the subsequent recovery of viscosity when the flow is discontinued" [KHAY12a]. The structural behaviour, build-up or breakdown, of cement-based materials is partially reversible over time. In addition to the reversible and truly thixotropic process, there is an irreversible structural change as time elapses after the initial contact between cement and mixing water.

The thixotropic behaviour of SCC plays a very important role in the industry. During placing, the material behaves indeed as a fluid but if cast slowly enough or if at rest, it builds up an internal structure and has the ability to withstand the load from concrete cast above it without increasing the lateral stress against the formwork [ROUS06a]. This phenomenon is going to be studied thoroughly in Chapter VIII of this document.

4.2 Approach to rheological analysis over time. Thixotropy and workability loss

As explained in Chapter III, the stress growth test with the ICAR rheometer was used to determine the static (at rest) yield stress. Furthermore, the slump flow test was used to measure the horizontal free-flow diameter (SF). Static yield stress and slump flow measurements were performed on a single concrete batch at the same time at different ages: at 15, 45 and 90 min from the cement-water contact (age) (Table VI-3). For the static yield stress test these ages correspond with 5, 30 and 45 min resting time (RT) respectively.

Table VI-3. Equivalence between the mix age and the time at rest in stress growth test

Age (min)	RT (min)
15	5
45	30
90	45

As the slump flow test was carried out at different ages on a concrete that had been remixed (30 s into the mixer), then the slump value is related to the intrinsic yield stress which will increase due to workability loss (non-reversible phenomenon). However, as the rheometer test was carried out after the concrete being to rest (from 15 to 45 min, RT30 min, and then from 45 to 90, RT45 min), it is used to evaluate the static yield stress. Therefore, in this case it will increase due to thixotropy (reversible phenomenon) and also workability loss.

Then, in terms of static yield stress at a given time (Eq. 9):

$$\tau_{0,c}(t) = \tau_{0,c}(t_0) + \Delta\tau_{0,c,workloss} + \Delta\tau_{0,c,thix} \quad (9)$$

Where:

$\tau_{0,c}(t_0)$ is the static yield stress of concrete at the reference time

$\tau_{0,c}(t)$ is the static yield stress of concrete at a given time t

$\Delta\tau_{0,c,workloss}$ is the increase of yield stress due to workability loss

$\Delta\tau_{0,c,thix}$ is the increase of yield stress due to thixotropy

However, in terms of slump flow at any given time t (Eq. 10):

$$SF_c(t) = SF_c(t_0) + \Delta SF_{c,workloss} \tag{10}$$

Being:

SF_c (t_0) is the slump flow of concrete at the reference time

SF_c (t) is the slump flow of concrete at a given time t

$\Delta SF_{c,workloss}$ is the decrease of slump flow due to workability loss

The relative variation will be (in terms of static yield stress) (Eq. 11):

$$\frac{\tau_{0,c}(t)}{\tau_{0,c}(t_0)} = 1 + \frac{\Delta\tau_{0,c,workloss}}{\tau_{0,c}(t_0)} + \frac{\Delta\tau_{0,c,thix}}{\tau_{0,c}(t_0)} \tag{11}$$

The relative variation will be (in terms of slump flow) (Eq. 12):

$$\frac{SF_c(t)}{SF_c(t_0)} = 1 + \frac{\Delta SF_{c,workloss}}{SF_c(t_0)} \tag{12}$$

Hence, as the slump flow ratio correlates with the yield stress ratio of a concrete that has been remixed, whereas the static yield stress ratio is calculated with the yield stress values obtained with a concrete that has been at rest in the rheometer container, both can be used to distinguish the non-reversible (workability loss due to the hydration process) from the reversible phenomenon (thixotropy).

4.3 Rheological analysis over time

The evolution of static yield stress and slump flow can be measured using the relative variations; that is, the ratios between the static yield stress at the age of 45 or 90 min and the static yield stress at 15 min (in this research, the reference time t_0 is 15 min) and, in the same way, the equivalent (inverse) slump flow ratios. That is (Eq. 13-14):

$$Ratio\ of\ yield\ stress\ (YS) = \frac{\tau_{0,c}(t\ min)}{\tau_{0,c}(t_0\ min)} \tag{13}$$

$$Ratio\ of\ slump\ flow\ (SF) = \left(\frac{SF(t\ min)}{SF(t_0\ min)}\right)^5 \tag{14}$$

Moreover, according to Eq. 5, under the same testing conditions it can be assumed that (Eq. 15):

$$\frac{\tau_{0,c}(t)}{\tau_{0,c}(t_0)} = \left[\frac{SF_c(t_0)}{SF_c(t)}\right]^5 \tag{15}$$

However, in this work the slump flow ratio measures the intrinsic yield stress (concrete remixed) while the rheometer measures the static yield stress (concrete at rest). The difference between the two is thixotropy, which is a physical reversible structural build-up developed in concrete at rest.

To understand the time-dependent evolution of SCRC, a rheograph including results at ages of 15, 45 and 90 min of baseline mixes produced with M1 method has been built (Figure VI-37). In this rheograph, the evolution of static yield stress and plastic viscosity can be calculated. Results of slump flow at different ages (Chapter V) can be used to determine the relative variations of this parameter.

Figure VI-38 shows the relative variations of yield stress and slump flow (*ratios of YS and SF*). Until the mix age of 45 min (resting time of 30 min), the relative variations remain the same for all concretes. However, at the mix age of 90 min (resting time of 45 min), this trend is only kept for replacement percentages up to 50% RCA.

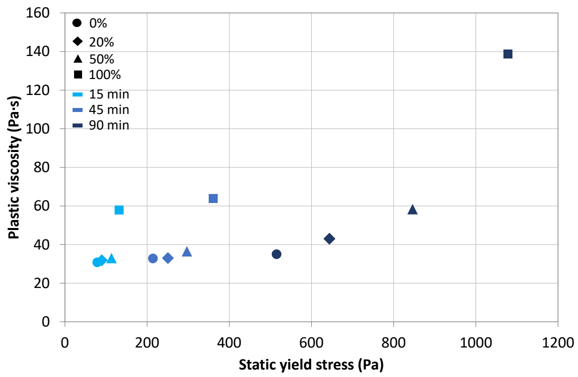


Figure VI-37. Rheograph of baseline mixes

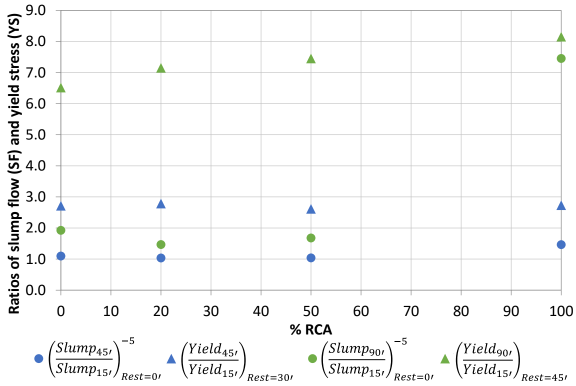


Figure VI-38. Ratios of SF and YS (baseline mixes)

At 45 min, the workability loss hardly exists as the SF ratio of all concretes is almost 1. Hence, the relative variations evaluated with the static yield stress at this same age essentially measure thixotropy, which, as it can be seen in Figure VI-38, is almost the same in all concretes.

At 90 min, it can be observed that the relative variations evaluated with the slump flow in SCRCs with replacement percentages up to 50% are similar to those of conventional concrete and they are low, which indicates, again, low workability losses. In these concretes, differences between the relative variations measured with the static yield stress and with the slump flow are also almost equal (although a slight increase in these differences with the replacement percentage can be observed). However, at 90 min, SCRC with 100% of replacement presents a relatively high variation evaluated with the slump flow, which shows a noteworthy workability loss at this age.

To further understand the rheological behaviour of SCRC over time, it is necessary to understand the time-dependent evolution of the effective w/c ratio. At the three testing times (or testing ages), the effective w/c ratio of SCRCs was calculated (Figure VI-39) considering that the recycled aggregate water absorption at 10 min had been compensated and that recycled aggregates will have absorbed at each given time the value from Figure III-15 (RCA water absorption evolution from 0 to 100 min) of Chapter III.

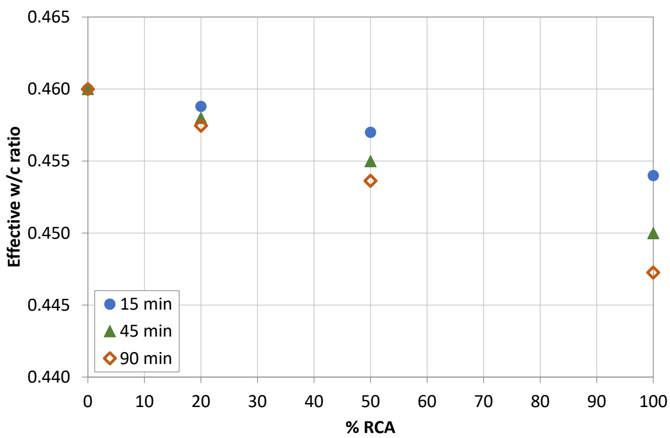


Figure VI-39. Evolution of $(w/c)_{ef}$ of SCRCs

These results state that, with the selected mixing protocol and with the design effective w/c ratio, SCC and SCRC are on the slight slope region of the "rheological variations – $(w/c)_{ef}$" curves at short times (15 and 45 min). Then, both recycled and conventional concretes show a similar evolution of rheological behaviour until 45 min, even the 100% concrete. This trend is maintained until 90 min when replacement percentages do not exceed 50%. These concretes with low replacement ratios show an effective w/c ratio that keeps on the slight slope region of their "rheological variations – $(w/c)_{ef}$" curves. However, the reduction in the effective w/c ratio at 90 min is more significant in 100% SCRC. In this case, its effective w/c ratio is on the high slope region of its "rheological variations - $(w/c)_{ef}$" curve (Figure VI-40) leading to different rheological behaviour over time.

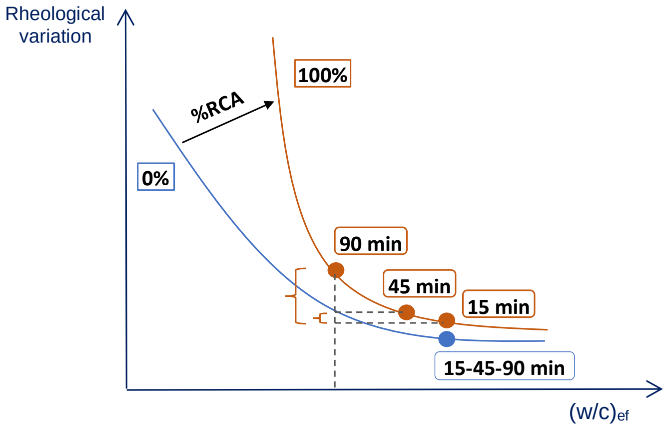


Figure VI-40. Rheological variations vs. Effective w/c ratio over time (SCC vs. SCRC)

To end this section, the previous analysis made with "Rheology" mixes will be confirmed by the results over time obtained with "Robustness" mixes (Figure VI-41, Figure VI-42, Figure VI-43, Figure VI-44, Figure VI-45, Figure VI-46, Figure VI-47, Figure VI-48, Figure VI-49, Figure VI-50, Figure VI-51 and Figure VI-52).

The time-dependent evolution of these mixes can be explained in a similar way to that of baseline mixes. From 15 to 45 min, higher rheological parameters are obtained as the replacement percentage increases. Again, in general, workability loss hardly exists and all mixes present a similar degree of thixotropy. Only the 100% SCRC with a decrease of its water content presents a significant workability loss. Mixes with water decreases are sited higher on the "rheological variations – $(w/c)_{ef}$" curves so, at 45 min, the SCRC100W- mix is being already moved on the high slope region of its high slope curve. Therefore, it can be concluded that (but for SCRC100W-) the evolution of SCRCs until 45 min is similar to the one of SCCs.

From 45 to 90 min, self-compacting recycled concretes with high replacement percentages show a different evolution since the high slope of their high "rheological variations – $(w/c)_{ef}$" curves is probably being reached.

Therefore, the differences seen between SCC and SCRC behaviour over time depend on the quantity of water compensated in the mixing protocol that determines the region of the "rheological variations – $(w/c)_{ef}$" curves where the concrete has been designed (near or far from the high slope region) (Figure VI-40). It is clear that the effective w/c ratio of SCRC evolves over time according to the evolution of the RCA water absorption. Then, it is more probable that the high slope region of the mentioned curves will be reached when high percentages of recycled aggregate are used, when SCRC is designed with a lower w/c ratio and/or when long term self-compacting behaviour is measured. In these cases, a different time-dependent rheological behaviour is expected from a SCRC than from a SCC, otherwise, the rheological behaviour over time of a SCRC will be similar to that of a SCC.

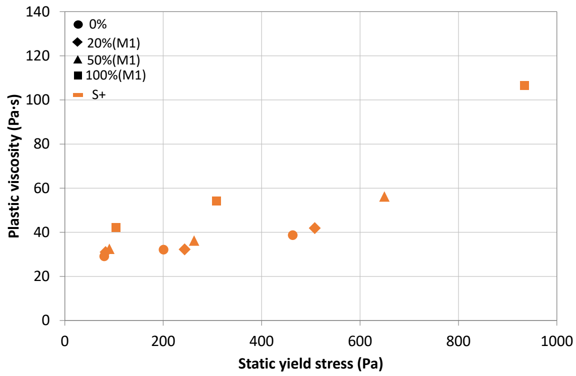


Figure VI-41. Rheograph of “S+” mixes

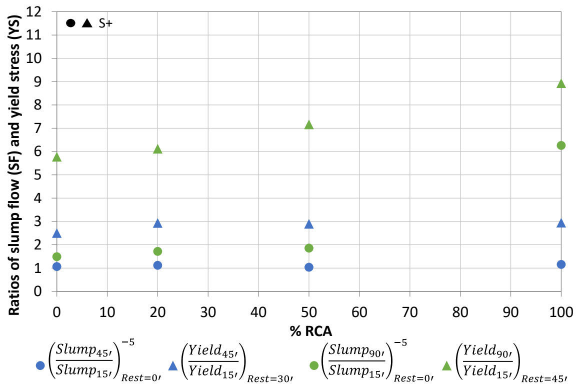


Figure VI-42. Ratios of SF and YS (“S+” mixes)

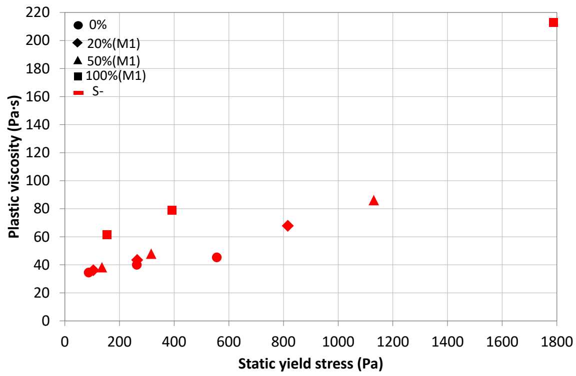


Figure VI-43. Rheograph of “S-” mixes

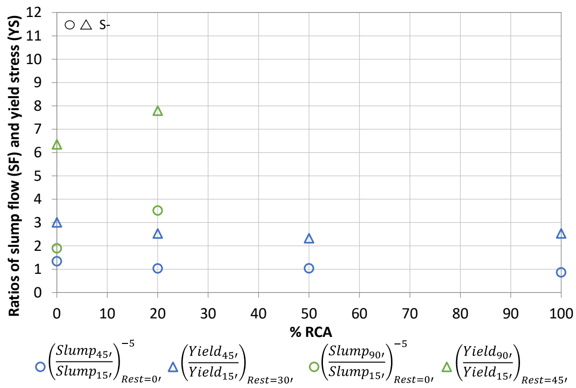


Figure VI-44. Ratios of SF and YS (“S-” mixes)

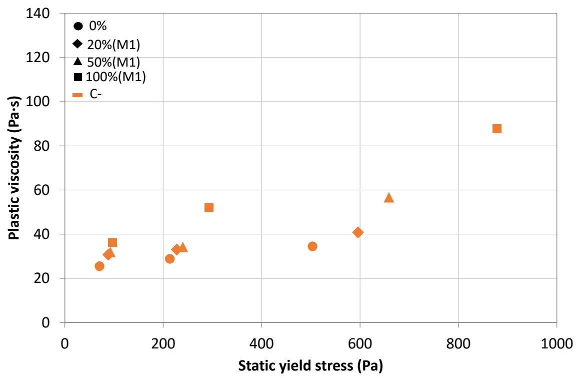


Figure VI-45. Rheograph of “C-” mixes

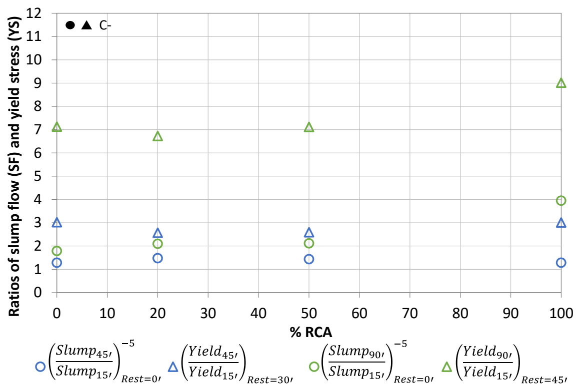


Figure VI-46. Ratios of SF and YS (“C-” mixes)

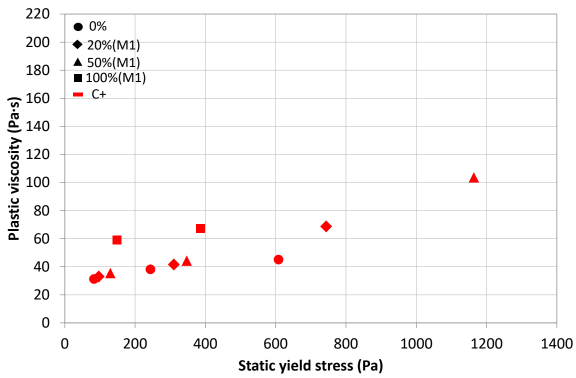


Figure VI-47. Rheograph of “C+” mixes

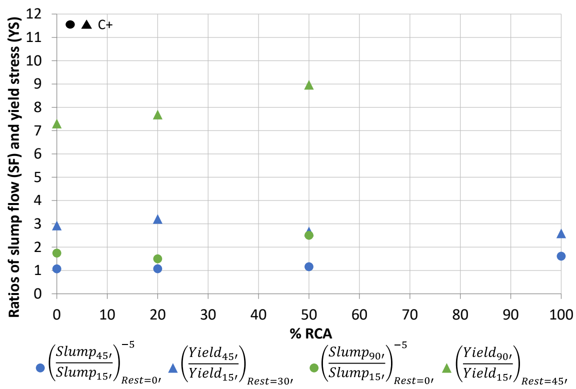


Figure VI-48. Ratios of SF and YS (“C+” mixes)

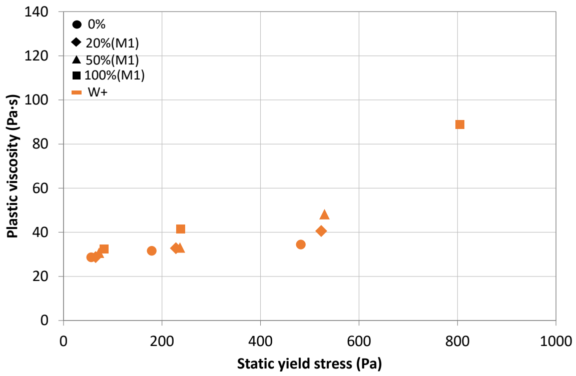


Figure VI-49. Rheograph of "W+" mixes

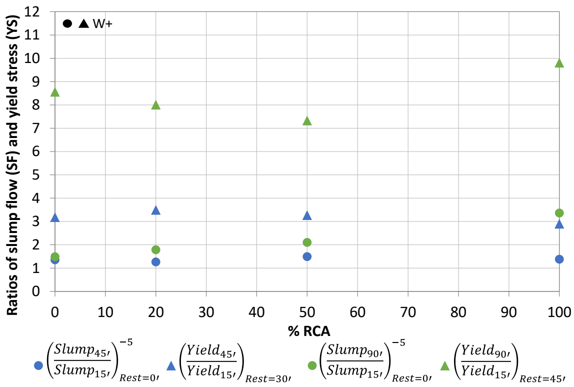


Figure VI-50. Ratios of SF and YS ("W+" mixes)

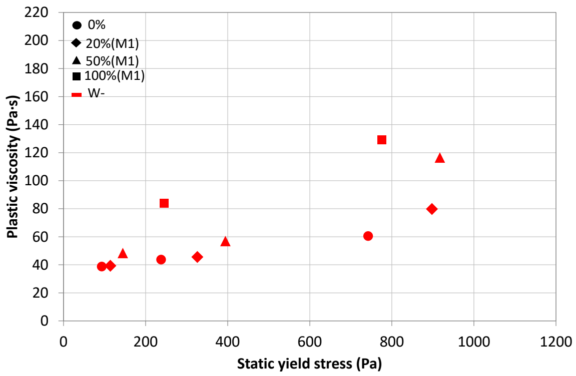


Figure VI-51. Rheograph of "W-" mixes

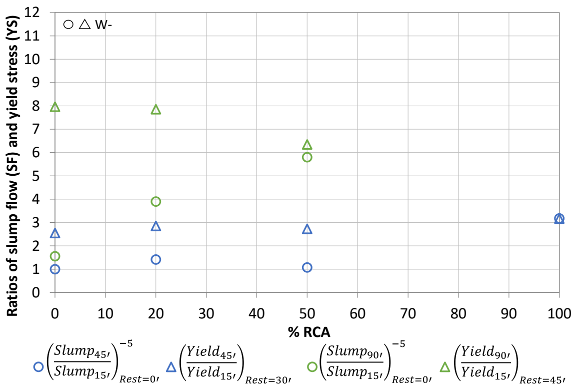


Figure VI-52. Ratios of SF and YS ("W-" mixes)

5 CONCLUSIONS

In this chapter, workability and rheology of self-compacting recycled concrete (SCRC) were analysed. Based on the results obtained, the following conclusions can be drawn:

- It can be stated that the same relationships between empirical parameters and between empirical parameters and rheological properties can be used for conventional and recycled self-compacting concretes. The same tendency was observed in SCC as well as in SCRC regarding all relationships. All the limits established to the empirical parameters in SCC are suitable for SCRC. Only the PJ parameter seems to be too strict to analyse the blocking behaviour in SCRC. In this work, a PJ maximum value of 25 mm was determined. Moreover, according to all the obtained results and in agreement with other authors, none of the empirical tests was found to adequately cover all key characteristics of SCRC as a single test, and there is no combination of tests that has achieved universal approval.

- The analysis of rheological behaviour showed that the specificity of SCRC lies in the quantity of extra water necessary to compensate for the recycled aggregate absorption during the mixing protocol, which affects the effective water to cement ratio, and in the intrinsic characteristics of recycled coarse aggregate (shape, texture and fines content). In this work, mainly the rough texture (since both natural and recycled coarse aggregates are crushed-shaped) and the fines content in the recycled aggregate and generated during mixing by the wear of old adhered mortar change the baseline mortar. All these singularities lead to different "rheological variations – $(w/c)_{ef}$" and "rheological property – $\emptyset/\emptyset_{max}$" curves in a SCRC compared to a SCC.

- Finally, the differences obtained between SCC and SCRC behaviour over time depend on the quantity of water compensated in the mixing protocol that determines the region of the "rheological variations – $(w/c)_{ef}$" curves where the concrete has been designed (near or far from the high slope region). It is clear that the effective w/c ratio of SCRC evolves over time according to the evolution of the RCA water absorption. Then, it is more probable that the high slope region of the mentioned curves will be reached when high percentages of recycled aggregate are used, when SCRC is designed with a lower w/c ratio and/or when long term self-compacting behaviour is measured. In these cases, a different time-dependent rheological behaviour is expected from a SCRC than from a SCC, otherwise, the rheological behaviour over time of a SCRC will be similar to that of a SCC.

CHAPTER VII
Analysis of self-compacting recycled concrete fresh behaviour: Robustness

1 INTRODUCTION AND OBJECTIVES

In this chapter, SCRC robustness is analysed. As defined in Chapter V, the word *robustness* refers to the capacity of concrete to maintain its properties when the quantities of materials used in its production are changed. In this research, the modifications imposed were introduced, in an independent way, to the water (±W = ±3%), the superplasticiser (±S = ±5%) and the cement (±C = ±3%). These percentages were selected to be representative of possible deviations in industrial production and taking into account tolerances for materials weighing established by Eurocode standard [EURO04].

All tests carried out (Chapter V) indicate that mixes with low replacement ratios are more robust than the ones produced with high substitution percentages, i.e. they maintain the rheological parameters over time without almost any variations, unlike the 100% substitution mixes. So, this chapter is focused on understanding the reason of this behaviour and, then, on determining which parameters affect SCRC robustness to a greater extent.

One of the main parameters that affects the rheological behaviour of SCC in general, and SCRC in particular, is the water control. Therefore, it is expected that SCRC robustness will depend on this parameter. In order to evaluate this possibility, an analysis of SCRC robustness will be made through the calculation of sensitivity parameters. After this analysis, a statistical approach to SCRC robustness is carried out. The aim is to determine which tests provide more sensitivity when the robustness of a SCC mix in general, and a SCRC mix in particular, is evaluated.

Therefore, robustness is analysed using the sensitivity parameters obtained with mixes made with M1 and M3 methods at 15 and 45 min, avoiding any possible workability loss (90 min) and segregated mixes (M2 method). The statistical approach is focused on achieving the best selection of reliable SCRC properties to evaluate its robustness, so, in this case results at 90 min are also used.

2 SENSITIVITY PARAMETERS APPROACH TO SCRC ROBUSTNESS

The analysis is focused on the amplitude of variation in static yield stress, plastic viscosity and empirical results at a mix age of 15 and 45 min. This amplitude of variation was calculated as the distance between both the increase and the decrease of yield stress, plastic viscosity and empirical results regarding the baseline value (in percentage). These values are the sensitivity parameters.

To calculate the sensitivity parameters with the empirical results, the time of the V-funnel test (tv) and the J-Ring blocking step (PJ) were not considered. As explained in previous chapters, it had been concluded that the V-funnel test results were not conclusive enough, agreeing with many other authors that do not recommend it for workability control, and the 10 mm maximum limit of PJ parameter was concluded to be too strict to analyse the passing ability. Therefore, in this case, each sensitivity parameter is the average of the amplitude of variation of the following empirical results at 15 and 45 min: SF, t500, PL, t500J, SFJ and SR.

Regarding sensitivity parameters of static yield stress and plastic viscosity, they were calculated as the average of the amplitude of variation in these properties at 15 and 45 min. In Figure VII-1, Figure VII-2 and Figure VII-3, the sensitivity parameters for each concrete when water, superplasticiser and cement were modified are shown.

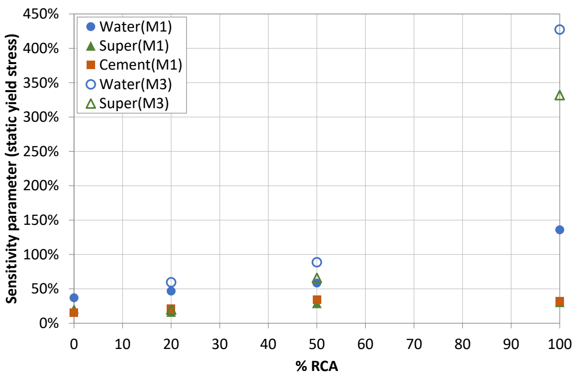


Figure VII-1. Sensitivity parameters of static yield stress (average 15 and 45 min)

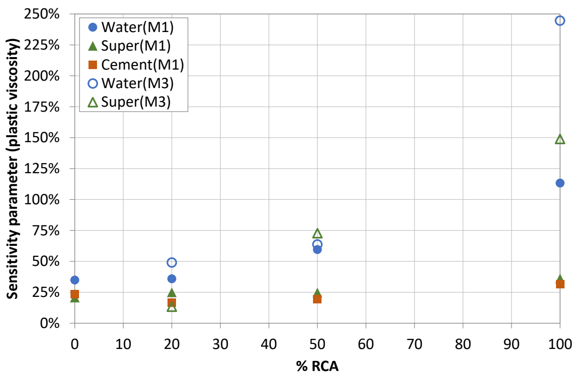


Figure VII-2. Sensitivity parameters of plastic viscosity (average 15 and 45 min)

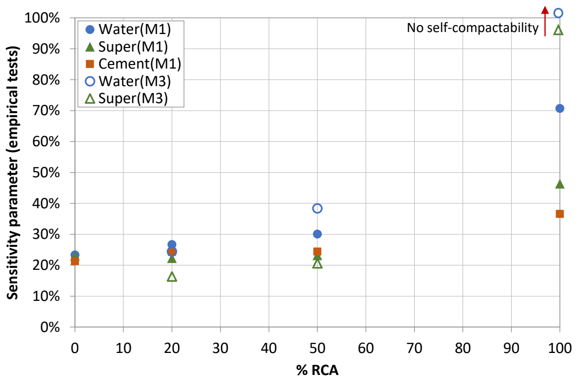


Figure VII-3. Sensitivity parameters of empirical tests (average 15 and 45 min)

The analysis of the sensitivity parameters confirms that mixes with low replacement ratios are more robust (present lower sensitivity parameters) than the ones produced with high substitution percentages. Moreover, mixes made using the M3 method present higher sensitivity parameters than the ones made with M1 method when high replacement percentages are used. In order to explain these results, the sensitivity parameters obtained with each material variation are analysed.

Regarding changes in water dosage, it is known that the total quantity of mixing water is a key factor that affects robustness of SCC [NAJI11]. Then, reducing or increasing the amount of water is expected to have a significant influence on self-compactability [GETT09]. Agreeing with these authors, as seen in Figure VII-1, Figure VII-2 and Figure VII-3, changes in water provide the highest values of the sensitivity parameters (higher than those obtained with superplasticiser or cement changes), especially as the % of RCA increases.

Of course, more water involves an increase in the w/c ratio and also a decrease in the solid volume fraction, Ø. On the contrary, less water involves a decrease in the first parameter and an increase in the second one. It can be seen that an increase in water will not affect the fresh parameter to the same extent as a decrease. In the first case, changes will move the mix towards the slight slope region of the curves (Figure VII-4 and Figure VII-5), while, in the second one, they will move it towards the high slope region of them.

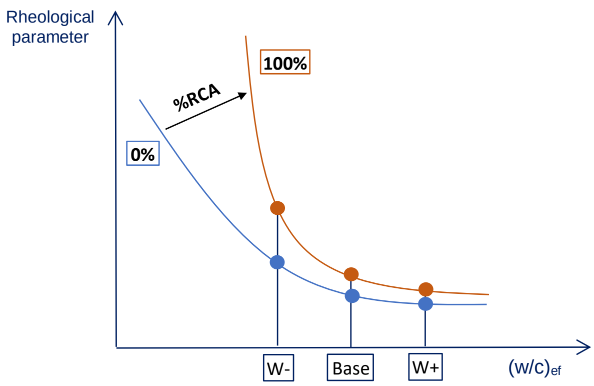


Figure VII-4. Rheological parameter – $(w/c)_{ef}$ (water changes)

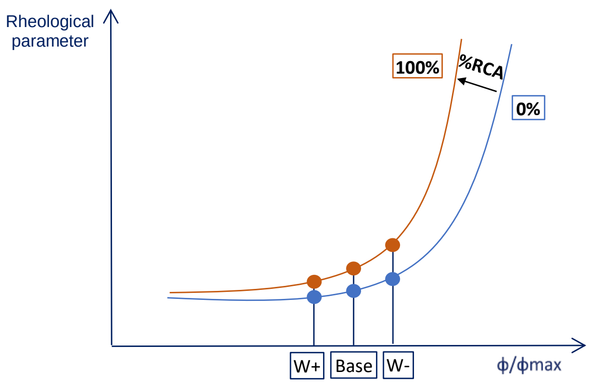


Figure VII-5. Rheological parameter – $Ø/Ø_{max}$ (water changes)

Concerning the recycled aggregate content, as concluded in the previous chapter, the relationship between a rheological parameter and the effective w/c ratio and a rheological parameter and the $Ø/Ø_{max}$ ratio are different as a function of the percentage of recycled coarse aggregate. Self-compacting recycled concrete shows curves with higher slope than the ones of conventional self-compacting concrete and this slope increases with the increase in the replacement percentage. Due to this high slope of the curves, reductions in water lead to higher changes in rheology. Therefore, these reductions significantly move the recycled mix through the high slope region of their high slope curves producing significant increases in rheological parameters and then, significant growth in the sensitivity parameter related to water variations. This effect can be seen clearly when high replacement percentages are used and it is the cause of the low robustness of self-compacting recycled concrete with high content of recycled aggregate.

Regarding the changes in superplasticiser dosage, in Figure VII-1, Figure VII-2 and Figure VII-3 it can be seen that these modify fresh behaviour parameters to a lesser extent than water changes. In fact, as aforementioned, the variations in superplasticiser imply very little volumetric quantities and, therefore, these barely involve changes in the effective w/c ratio and they hardly alter the $Ø/Ø_{max}$ ratio. The effect of the superplasticiser should be evaluated taking into account its chemical activity. In this work, all SCRCs show sensitivity parameters lower than the ones obtained with water changes. In any case, self-compacting recycled concretes with high replacement percentages show higher sensitivity parameters, evaluated with superplasticiser changes, than those obtained with conventional SCC.

Moreover, in both cases (water and superplasticiser), mixes made with the M3 method show higher sensitivity parameters than those mixes made with M1 method when high replacement percentages are used. When aggregates are used with a moisture content, the control of water is more difficult and then, this fact negatively affects SCRC robustness, as other authors have previously concluded in conventional SCC [NAJI11].

Finally, Figure VII-1, Figure VII-2 and Figure VII-3 also show the results of the cement amount variations, which follow the same trend as those obtained with the water variations. However, water changes influence the SCRC behaviour to a greater extent than cement changes. As explained in the previous chapter, this is due to the different effect in $(w/c)_{ef}$ and in $Ø/Ø_{max}$ that water and cement variations produce. In the first case (water), both effects are additive and in the second one (cement), they counteract leading to influence rheological values to a less extent. This implies that sensitivity parameters obtained with cement variations are lower than those obtained with water changes. Therefore, it can be stated that water is the key factor that affects SCRC robustness.

Furthermore, it can be concluded that SCRC is less robust than SCC. This is due to the fact that SCRC presents "rheological parameter – $(w/c)_{ef}$" and "rheological parameter – $Ø/Ø_{max}$" curves with higher slope than the ones of conventional SCC. Then, when high percentages of recycled aggregate are used, it is more probable to reach the high slope region of high slope curves causing high yield stress changes (and similarly high plastic viscosity changes and high empirical parameters changes). Additionally, the use of aggregates with a moisture content makes it more difficult to design robust SCRCs, as it occurs with SCCs.

Finally, SCRCs robustness will depend on the quantity of water compensated in the mixing protocol and on the region of the "rheological parameter – $(w/c)_{ef}$" curve where the concrete has been designed (near or far from the high slope).

3 STATISTICAL APPROACH TO SCRC ROBUSTNESS

Taking into account the work of Naji et al. [NAJI11] on conventional SCC, Kendall's coefficient of concordance and Spearman's rank correlation can be used to evaluate SCRC robustness and to select adequate concrete properties that could be measured to determine it. Therefore, this will be the aim of this part of the work.

As aforementioned, in this statistical approach, results of "Rheology" and "Robustness" phases were used. When water and superplasticiser variations are analysed, mixes were produced with M1 and M3 methods. When cement variations are analysed, only M1 method was used. The results of rheology and workability over time (at 15, 45 and 90 min) have been used for this statistical approach.

3.1 Methodology

Kendall's coefficient of concordance is a measure of the agreement among several *k* "judges" used to assess a characteristic of a given set of *n* objects. The method is used to evaluate the degree of agreement among several "judges" [KEND39].

The methodology used in this work is summarized in Figure VII-6.

In this study, *n* (the objects to be assessed) are the different mixes characterised by their recycled aggregate percentage (0, 20, 50 or 100%) and the mixing method (M1 or M3). Therefore, when water and superplasticiser variations are imposed, M1 and M3 methods are used and then *n* = 7. However, when cement variations are analysed, only M1 method is used, then, in this case, *n* = 4.

Each object (*i* object, with *i* from 1 to *n*) is going to be ranked using different "judges" as assessors or a single judge applying different criteria. Then, a rank $R_{i,j}$, with i from 1 to *n* and with *j* from 1 to *k*, is obtained in each object for each judge based on the coefficients of variation obtained with each judge.

In this work, when water and superplasticiser variations are imposed, 31 properties were considered as the "judges of robustness" (*k* = 31) and the coefficients of variation (COVs) obtained with each judge were used to rank the seven mixes (n=7). In the case of cement variations, 26 properties were considered (*k* = 26) to rank the four mixes (*n* = 4). Each COV is obtained for each object (mix) and for each judge (property) with the results of the baseline mix ("0") and of the same mix with the two material variations (increase, "+", and decrease, "-"). Therefore, these COVs are used to rank each object (mix) within each judge (property), $R_{i,j}$.

The result of the judgment (concrete robustness) can be obtained summing, in each object (mix), the ranks ($R_{i,j}$) gotten with each judge (property) (Eq. 1).

$$SR_i = \sum_{j=1}^{j=k} R_{i,j} \quad i = 1 \cdots n \tag{1}$$

This result (SR_i) can be normalized and then used to define SCRC robustness. This "normalized sum of ranking" (0-100%) (Eq. 2) will be used to rank the objects according to their robustness, "Rrb" (from more robust to less robust). Moreover, this can be used to define a category (high, medium, low) that classifies the robustness of each SCRC mix [NAJI11].

$$Normalized\ sum\ of\ ranking\ (\%) = \frac{(SR_{max} - SR_i)}{(SR_{max} - SR_{min})} 100 \tag{2}$$

Being:

$$SR_{max} = \max(SR_i) \quad i = 1 \cdots n \tag{3}$$

$$SR_{min} = \min(SR_i) \quad i = 1 \cdots n \tag{4}$$

On the left of the Figure VII-6, a flow chart is shown to summarize this part of the methodology.

Once the characteristic (robustness) has been assessed, it is necessary to be sure that there is agreement among the "judges" used. To check this, the significance of Kendall's coefficient has to be evaluated.

For this purpose, the Kendall's coefficient (*W*) is calculated for the sample. To evaluate its significance, a significance level (α) is chosen and then the critical value of *W* (*W**) is calculated for this significance level. If the observed *W* is greater than or equal to the critical value *W**, then the null hypothesis (there is no agreement among the "judges") may be rejected at that level of significance, i.e. the "judges" are in agreement (there is concordance among them) in the assessment of the characteristic (robustness).

Therefore, firstly, the Kendall's coefficient is calculated as follows:

$$W = \frac{S}{\frac{1}{12} \cdot k^2 \cdot (n^3 - n)} \tag{5}$$

Being:

$$S = \sum_{i=1}^{n}(SR_i - SR)^2 \quad (6)$$

$$SR = \frac{(n+1)\cdot k}{2} \quad (7)$$

Then, to test whether an observed value of *W* is significant, it is necessary to consider the distribution of *W*. The actual distribution of *W* is irregular for low values of *k* and *n*, and likely to be quite irregular for moderate values [KEND39].

Regarding small samples, the distribution of *W* under H_o (null hypothesis, the assumption that the judges are in disagreement) has been worked out and the critical values of Kendall's coefficient (W^*) can be obtained taking into account the approximation based on Fisher's *z*-distribution with ν_1 and ν_2 degrees of freedom (Eqs. 8-10). The "*z*" values have been tabled for the following different significance levels, $\alpha = 0.05$ and $\alpha = 0.01$ [KEND90].

$$z = \frac{1}{2} log_e \frac{(k-1)W}{1-W} \quad (8)$$

$$\nu_1 = n - 1 - \frac{2}{k} \quad (9)$$

$$\nu_2 = (k-1)\nu_1 \quad (10)$$

For large samples, Friedman's test can be used to determine the significance of *W*. The Friedman's test statistic is distributed approximately as chi-square (χ^2), with (*n* - 1) degrees of freedom (Eq. 11). In this case, also, for a desired level of significance and a particular value of *n,* under the null hypothesis (H_o), the critical values (W^*) can be obtained.

$$\chi^2 = k(n-1)W \quad (11)$$

When *W* equals or exceeds the critical value W^* obtained for a desired level of significance, the null hypothesis (the assumption that the judges are in disagreement) may be rejected. That is, the *k* "judges" (properties) are in agreement with each other and it can be concluded that there is a good consensus among them concerning the evaluation of the characteristic (robustness) of the *n* objects (mixes).

On the right of the Figure VII-6, the flow chart shows this part of methodology.

Lastly, when the significance of Kendall's coefficient was evaluated, the correlation between the rankings of an individual "judge" ($R_{i,j}$) and the final ranks of the objects, "Rrb", has to be assessed. To do so, Spearman's correlation test can be used.

Spearman's correlation test calculates the Spearman's rank correlation coefficient or Spearman's ρ_s. It is a non-parametric measure of statistical correlation between two ranked variables [SPEA04], and it can be expressed as follows:

$$\rho_{s,j} = 1 - \frac{6\cdot\sum_{i=1}^{n}\left(R_{i,j} - Rrb_i\right)^2}{n\cdot(n^2-1)} \quad (12)$$

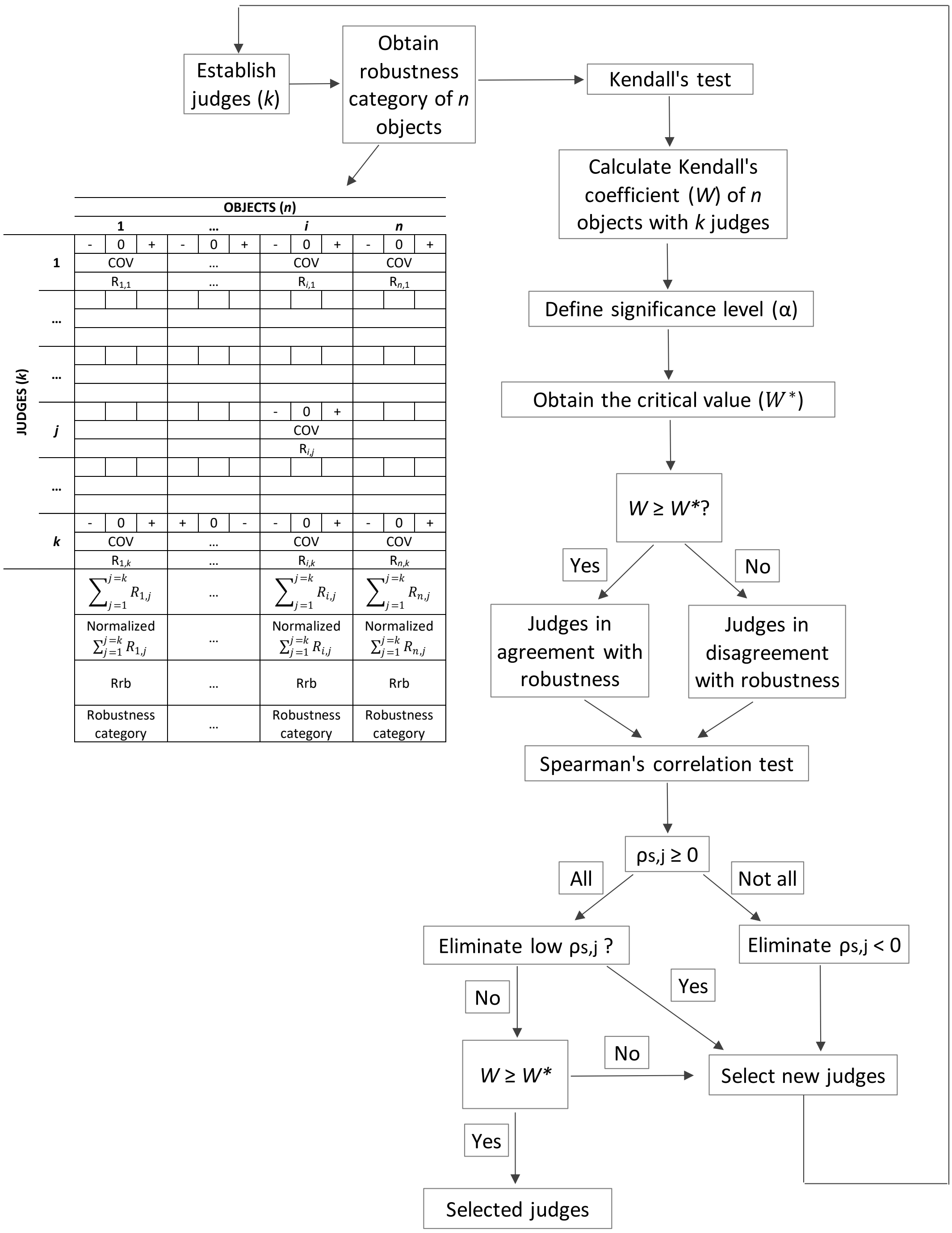


Figure VII-6. Flow chart of statistical approach methodology

Spearman's $\rho_{s,j}$ ranges between -1 and 1 and measures the correlation between rankings obtained with an individual judge ($R_{i,j}$) and the final ranks of the objects, "Rrb". A positive value of $\rho_{s,j}$ implies a positive correlation among the two series of rankings. On the contrary, a negative $\rho_{s,j}$ value indicates a no correlation between them.

Therefore, the result of this test allows us to eliminate those judges which provide no correlation and/or those which provide a low correlation. In this way, the number of judges may be reduced, simplifying the characteristic assessment. In any case, if the number of judges is changed, it is necessary to check that Kendall's coefficient maintains a value higher than the critical one according to the desired level of significance. Once this has been done, it can be concluded that the selection of judges that provide the best correlation to assess the characteristic is achieved.

3.2 Evaluation of SCRC robustness

The study of robustness of mixes produced with M1 and M3 method (*n* = 7, SCRC0, SCRC20M1, SCRC50M1, SCRC100M1, SCRC20M3, SCRC50M3, SCRC100M3) has been made using water variations (W+, 0, W-, that corresponds to +3%, base, -3%) and superplasticiser variations (S+, 0, S-, that corresponds to +5%, base, -5%). In this case, thirty-one properties of SCRC were used as "judges". These properties include six rheological properties, three mechanical ones and twenty-two workability parameters. Therefore, when the study was made applying water and superplasticiser variations, seven mixes (*n* = 7, SCRC0, SCRC20M1, SCRC50M1, SCRC100M1, SCRC20M3, SCRC50M3, SCRC100M3) were analysed with 31 properties (k=31).

Robustness of mixes produced with M1 method (*n* = 4, SCRC0, SCRC20M1, SCRC50M1, SCRC100M1) were also studied using cement variations (C+, 0, C-, that corresponds to +3%, base, -3%). In this case, twenty-six properties were used as "judges". These properties include six rheological properties, three mechanical ones and seventeen workability parameters. Therefore, when the study was made applying cement variations, four mixes (*n* = 4, SCRC0, SCRC20M1, SCRC50M1, SCRC100M1) were analysed with 26 properties (k=26).

In the three cases (water, Table VII-1, superplasticiser, Table VII-2, and cement variations, Table VII-3), the COVs obtained with each property were calculated for each mix. Based on the COV values, the SCRC mixes were ranked. The mix with the lowest COV value is the mix that presents the best level of robustness, so this mix will be ranked with the number "1" and so on.

Table VII-1, Table VII-2 and Table VII-3 present the rheological, mechanical and workability properties obtained in mixes where water, superplasticiser and cement variations were imposed, respectively. The COV values obtained with each property and the corresponding ranking assigned to each mix are also presented. If a property value does not appear on the tables, this means that it was not possible to develop the test to measure it due to the loss of self-compactability. Then, this mix was ranked with the highest ranking value.

Table VII-1. Test results and ranking of SCRCs according to COV of properties at different water levels

		SCRC0			SCRC20M1			SCRC50M1			SCRC100M1			SCRC20M3			SCRC50M3			SCRC100M3		
τ_0 (15')	W-; 0; W+	93.2	79.0	56.3	114	90.0	65.3	145	114	72.3	245	132	82.0	152	107	61.1	204	147	70.6	712	136	140
	COV (%)	24.5			27.3			32.9			54.4			42.6			47.7			101		
	Rank	1			2			3			6			4			5			7		
μ_{pl} (15')	W-; 0; W+	38.7	30.8	28.7	39.3	31.8	28.7	48.4	33.0	31.0	83.9	57.9	32.4	47.5	34.5	29.1	53.3	45.7	34.8	180	52.4	51.2
	COV (%)	16.2			16.3			25.8			44.3			25.5			20.8			78.4		
	Rank	1			2			5			6			4			3			7		
τ_0 (45')	W-; 0; W+	238	214	179	326	251	228	395	297	237	776	361	238	335	262	246	533	309	266	1607	328	449
	COV (%)	14.0			19.1			25.8			61.4			16.9			38.8			88.8		
	Rank	1			3			4			6			2			5			7		
μ_{pl} (45')	W-; 0; W+	43.7	32.8	31.6	45.6	33.0	32.8	56.9	36.5	33.1	129	63.7	41.4	49.8	38.7	32.4	84.3	50	40.8	225	60.7	77.4
	COV (%)	18.6			19.7			30.6			58.4			21.8			39.3			74.7		
	Rank	1			2			4			6			3			5			7		
τ_0 (90')	W-; 0; W+	742	515	482	898	644	523	917	846	530		1079	804	1397	587	474	2714	1076	1077		1119	3053
	COV (%)	24.4			27.8			26.9						61.5			58.3					
	Rank	1			3			2			6			5			4			7		

		SCRC0			SCRC20M1			SCRC50M1			SCRC100M1			SCRC20M3			SCRC50M3			SCRC100M3		
μ_{pl} (90')	W-; 0; W+	60.5	35.0	34.4	79.8	43.0	40.6	116	58.3	48.2		139	88.8	109	54.0	47.1	123	92.4	65.7		140	257
	COV (%)	34.4			40.3			49.6						48.4			30.6					
	Rank	2			3			5			6			4			1			7		
$f_{c,3d}$	W-; 0; W+	68.6	68.3	67.2	66.5	64.2	64.8	64.5	64.2	63.8	60.6	59.9	59.5	66.9	66.8	66.3	64.9	64.8	63.9	63.1	60.0	59.1
	COV (%)	1.1			1.8			0.5			1.0			0.4			0.8			3.4		
	Rank	5			6			2			4			1			3			7		
$f_{c,7d}$	W-; 0; W+	74.9	73.8	73.2	74.4	70.2	70.2	68.1	68.1	67.9	66.6	64.2	64.9	71.4	70.9	70.7	69.2	69.5	69.3	67.5	65.3	61.6
	COV (%)	1.2			3.4			0.2			1.9			0.5			0.3			4.6		
	Rank	4			6			1			5			3			2			7		
$f_{c,28d}$	W-; 0; W+	80.8	80.4	79.6	80.5	76.9	75.5	76.3	75.5	73.6	70.4	70.5	70.0	80.8	79.0	79.0	76.1	75.9	74.2	72.0	69.3	69.3
	COV (%)	0.8			3.3			1.9			0.4			1.3			1.4			2.2		
	Rank	2			7			5			1			3			4			6		
t500 (15')	W-; 0; W+	1.59	1.45	1.1	2.26	1.96	1.34	2.57	2.38	1.51	5.45	4.07	2.95	2.4	2.29	1.43	3.81	2.59	1.7		4.41	3.14
	COV (%)	18.3			25.3			26.2			30.1			26.0			39.2					
	Rank	1			2			4			5			3			6			7		
SF (15')	W-; 0; W+	770	815	850	745	745	820	700	710	815	630	680	720	710	715	780	640	705	750		660	650
	COV (%)	4.9			5.6			8.6			6.7			5.3			7.9					
	Rank	1			3			6			4			2			5			7		
tv (15')	W-; 0; W+	29.5	23.7	18.4	39.0	25.8	25.7	40.6	30.6	24.9	43.1	33.2	26.4	34.0	24.8	23.9	47.3	32.5	27.6		22.0	14.6
	COV (%)	23.3			25.5			24.8			24.5			20.3			28.5					
	Rank	2			5			4			3			1			6			7		
PL (15')	W-; 0; W+	0.85	0.90	0.90	0.82	0.87	0.90	0.74	0.88	0.90	0.57	0.83	0.89	0.84	0.86	0.92	0.67	0.82	0.91		0.79	0.76
	COV (%)	3.3			4.7			10.4			22.3			4.8			15.2					
	Rank	1			2			4			6			3			5			7		
t500J (15')	W-; 0; W+	3.00	2.5	1.60	3.03	2.96	1.76	4.46	3.73	2.37	9.64	4.25	2.64	3.77	3.22	2.33	5.07	3.91	2.40		4.50	3.96
	COV (%)	29.9			27.6			30.1			66.5			23.4			35.3					
	Rank	3			2			4			6			1			5			7		
SFJ (15')	W-; 0; W+	750	820	850	730	750	845	670	700	775	535	675	745	695	725	735	620	690	730		660	665
	COV (%)	6.3			7.9			7.6			16.5			2.9			8.2					
	Rank	2			4			3			6			1			5			7		
PJ (15')	W-; 0; W+	12	10	9	18	13	8	23	19	16	31	20	18	16	14	12	23	17	13		20	20
	COV (%)	14.8			38.5			18.2			30.4			14.3			28.5					
	Rank	2			6			3			5			1			4			7		
SR	W-; 0; W+	11.1	13.6	15.3	8.9	13.1	13.5	7.5	11.5	13.4	2.7	3.5	7.6	7.3	10.6	12.9	5.6	9.4	11.8	0.02	4.8	2.0
	COV (%)	15.7			21.4			27.9			57.5			27.9			34.9			105		
	Rank	1			2			4			6			3			5			7		
t500 (45')	W-; 0; W+	2.39	1.95	1.9	3.3	2.31	2.21	3.53	2.75	2.57	8.77	5.41	3.53	3	2.58	2.48	4.13	3.46	3.01		5.71	2.95
	COV (%)	12.9			23.1			17.3			44.9			10.3			15.9					
	Rank	2			5			4			6			1			3			7		
SF (45')	W-; 0; W+	770	800	800	695	740	785	690	705	755	500	630	675	670	715	750	620	700	725		620	610
	COV (%)	2.2			5.9			4.6			15.1			5.6			8.0					
	Rank	1			4			2			6			3			5			7		
tv (45')	W-; 0; W+	33.3	24.7	21.2	45.5	35.2	22.5	59.3	45.3	33.0		42.1	40.2	34.9	28.1	26.6	43.9	34.1	31.5		32.9	21.3
	COV (%)	23.6			33.5			28.7						14.9			17.9					
	Rank	3			5			4			6			1			2			7		
PL (45')	W-; 0; W+	0.83	0.90	0.90	0.81	0.82	0.89	0.75	0.82	0.87	0.38	0.84	0.90	0.85	0.86	0.90	0.68	0.83	0.92		0.80	0.73
	COV (%)	4.6			5.2			7.4			40.3			3.0			15.3					
	Rank	2			3			4			6			1			5			7		

		SCRC0			SCRC20M1			SCRC50M1			SCRC100M1			SCRC20M3			SCRC50M3			SCRC100M3		
t500J (45')	W-; 0; W+	3.37	2.47	1.75	4.20	3.17	2.38	5.01	4.59	2.43		6.00	4.21	4.63	3.49	2.82	6.09	5.08	3.50		6.59	9.65
	COV (%)	32.1			28.1			34.5						25.1			26.7					
	Rank	4			3			5			6			1			2			7		
SFJ (45')	W-; 0; W+	740	790	795	700	745	760	650	690	750		630	700	660	725	760	600	680	720		620	525
	COV (%)	3.9			4.2			7.2						7.1			9.0					
	Rank	1			2			4			6			3			5			7		
PJ (45')	W-; 0; W+	15	10	10	21	15	15	25	23	17		26	25	30	20	15	26	21	20		24	40
	COV (%)	24.7			20.4			19.2						35.3			14.4					
	Rank	4			3			2			6			5			1			7		
t500 (90')	W-; 0; W+	4.71	2.44	2.13	8.28	2.8	2.58	13.0	5.83	3.53			5.69	8.52	4.44	2.9	12.9	7	3.95			
	COV (%)	45.5			70.9			66.3						54.9			57.4					
	Rank	1			5			4			6			2			3			7		
SF (90')	W-; 0; W+	705	715	785	570	690	730	495	640	705		455	565	510	660	700	490	570	620		435	
	COV (%)	5.9			12.5			17.5						16.1			11.7					
	Rank	1			3			5			6			4			2			7		
tv (90')	W-; 0; W+	47.2	34.5	28.5	73.0	48.8	29.1		61.8	54.7			60		65	36.2		70.3	64.2			
	COV (%)	26.0			43.7																	
	Rank	1			2			4			6			5			3			7		
PL (90')	W-; 0; W+	0.54	0.75	0.82	0.38	0.60	0.91	0.38	0.62	0.77		0.56	0.51	0.51	0.73	0.74	0.21	0.60	0.89		0.17	
	COV (%)	20.7			42.8			33.3						19.7			60.2					
	Rank	2			4			3			6			1			5			7		
t500J (90')	W-; 0; W+	5.42	3.12	2.96	7.82	4.83	3.50	22.7	7.44	6.22			13.1	11.6	7.69	4.12		12.4	8.12			
	COV (%)	35.9			41.1			75.8						48.1								
	Rank	1			2			4			6			3			5			7		
SFJ (90')	W-; 0; W+	690	720	750	610	660	700	475	590	650			525	510	600	690		530	570			
	COV (%)	4.2			6.9			15.6						15.0								
	Rank	1			2			4			6			3			5			7		
PJ (90')	W-; 0; W+	25	17	16	35	26	25	59	35	32			50	49	35	25		44	35			
	COV (%)	26.2			19.7			35.2						33.2								
	Rank	2			1			4			6			3			5			7		
	SR_i	**57**			**104**			**116**			**171**			**80**			**124**			**216**		
	Rrb	**1**			**3**			**4**			**6**			**2**			**5**			**7**		

Table VII-2. Test results and ranking of SCRCs according to COV of properties at different superplasticiser levels

		SCRC0			SCRC20M1			SCRC50M1			SCRC100M1			SCRC20M3			SCRC50M3			SCRC100M3		
τ_0 (15')	S-; 0; S+	87.6	79.0	80.2	105	90.0	83.0	136	114	90.7	155	132	105	128	107	88.3	181	147	98.9	524	136	163
	COV (%)	5.7			12.0			20.0			19.2			18.5			28.9			79.0		
	Rank	1			2			5			4			3			6			7		
μ_{pl} (15')	S-; 0; S+	34.5	30.8	29.1	36.1	31.8	31.0	38.3	33.0	32.5	61.4	57.9	42.1	35.7	34.5	33.6	65.8	45.7	40.9	125	52.4	57.9
	COV (%)	8.7			8.3			9.3			19.1			3.1			26.0			51.8		
	Rank	3			2			4			5			1			6			7		
τ_0 (45')	S-; 0; S+	264	214	201	265	251	244	316	297	263	392	361	308	265	262	264	522	309	287	1365	328	465
	COV (%)	14.6			4.3			9.3			12.0			0.7			34.8			78.3		
	Rank	5			2			3			4			1			6			7		

		SCRC0			SCRC20M1			SCRC50M1			SCRC100M1			SCRC20M3			SCRC50M3			SCRC100M3		
μ_{pl} (45′)	S-; 0; S+	40.0	32.8	32.1	43.5	33.0	32.3	47.9	36.5	36.2	79.1	63.7	54.2	46.0	38.7	38.1	93.8	50.0	48.3	185	60.7	82.5
	COV (%)	12.5			17.3			16.6			19.1			10.8			40.3			60.7		
	Rank	2			4			3			5			1			6			7		
τ_0 (90′)	S-; 0; S+	556	515	463	816	644	508	1131	846	650	1787	1079	934	825	587	456	1600	1076	908		1119	3541
	COV (%)	9.1			23.5			27.6			36.0			30.1			30.2					
	Rank	1			2			3			6			4			5			7		
μ_{pl} (90′)	S-; 0; S+	45.3	35.0	38.7	67.8	43.0	41.9	86.1	58.3	56.2	213	139	107	78.4	54.0	49.4	115	92.4	91.7		140	258
	COV (%)	13.1			28.8			25.0			35.7			25.7			13.1					
	Rank	2			5			3			6			4			1			7		
$f_{c,3d}$	S-; 0; S+	66.6	68.3	67.0	64.9	64.2	68.5	63.7	64.2	66.5	59.5	59.9	58.3	67.0	66.8	69.7	62.9	64.8	66.1	60.2	60.0	58.5
	COV (%)	1.3			3.4			2.3			1.4			2.3			2.5			1.6		
	Rank	1			7			4			2			5			6			3		
$f_{c,7d}$	S-; 0; S+	73.7	73.8	73.9	70.1	70.2	72.3	67.6	68.1	70.2	63.7	64.2	62.2	72.4	70.9	73.5	68.6	69.5	71.4	65.6	65.3	63.3
	COV (%)	0.2			1.7			2.0			1.6			1.8			2.03			1.9		
	Rank	1			3			6			2			4			7			5		
$f_{c,28d}$	S-; 0; S+	80.8	80.4	81.5	76.9	76.9	79.3	73.6	75.5	76.2	70.4	70.5	69.4	78.6	79.0	81.0	72.2	75.9	76.1	69.9	69.3	69.0
	COV (%)	0.73			1.8			1.75			0.9			1.6			2.9			0.7		
	Rank	2			6			5			3			4			7			1		
t500 (15′)	S-; 0; S+	1.47	1.45	1.41	2.27	1.96	1.51	2.77	2.38	2.07	6.47	4.07	2.9	2.53	2.29	1.59	2.68	2.59	1.7		4.41	4
	COV (%)	2.1			20.0			14.6			40.6			22.9			23.3					
	Rank	1			3			2			6			4			5			7		
SF (15′)	S-; 0; S+	790	815	820	720	745	780	695	710	730	568	680	700	695	715	725	670	705	700		660	620
	COV (%)	2.0			4.0			2.5			10.9			2.1			2.7					
	Rank	1			5			3			6			2			4			7		
tv (15′)	S-; 0; S+	39.1	23.7	21.2	38.4	25.8	16.2	34.8	30.6	19.7	27.8	33.2	21.1	32.8	24.8	18.7	24.5	32.5	23.2	37.0	22.0	21.0
	COV (%)	34.6			41.5			27.4			22.1			27.7			18.9			33.7		
	Rank	6			7			3			2			4			1			5		
PL (15′)	S-; 0; S+	0.89	0.90	0.91	0.84	0.87	0.89	0.81	0.88	0.84	0.69	0.83	0.83	0.82	0.86	0.90	0.79	0.82	0.83	0.24	0.79	0.82
	COV (%)	1.1			2.9			4.2			10.3			4.7			2.6			53.0		
	Rank	1			3			4			6			5			2			7		
t500J (15′)	S-; 0; S+	3.44	2.5	1.90	3.84	2.96	2.15	4.88	3.73	2.32	10.4	4.25	4.00	3.38	3.22	2.90	4.18	3.91	3.62		4.50	5.07
	COV (%)	29.7			28.3			35.2			58.3			7.8			7.2					
	Rank	4			3			5			6			2			1			7		
SFJ (15′)	S-; 0; S+	780	820	820	710	750	815	680	700	770	550	675	705	720	725	755	665	690	715		660	620
	COV (%)	2.9			7.0			6.6			12.8			2.6			3.6					
	Rank	2			5			4			6			1			3			7		
PJ (15′)	S-; 0; S+	12	10	7	25	13	9	30	19	13	33	20	19	24	14	12	23	17	15		20	23
	COV (%)	26.0			53.1			41.7			31.6			37.5			23.4					
	Rank	2			6			5			3			4			1			7		
SR	S-; 0; S+	12.8	13.6	15.1	11.0	13.1	13.3	11.1	11.5	13.1	2.4	3.5	8.3	9.9	10.6	12.7	7.9	9.4	11.1	0.0	4.8	2.9
	COV (%)	8.5			9.8			9.2			66.6			13.2			16.5			94.5		
	Rank	1			3			2			6			4			5			7		
t500 (45′)	S-; 0; S+	3.09	1.95	1.58	3.15	2.31	1.81	3.78	2.75	2.59	5.72	5.41	3.22	3.32	2.58	2.43	3.65	3.46	2.6		5.71	4.5
	COV (%)	35.7			27.9			21.2			28.5			17.2			17.3					
	Rank	6			4			3			5			1			2			7		
SF (45′)	S-; 0; S+	745	800	810	715	740	765	690	705	725	585	630	680	690	715	795	660	700	790		620	610
	COV (%)	4.5			3.2			2.5			7.5			7.4			9.3					
	Rank	3			2			1			5			4			6			7		

		SCRC0			SCRC20M1			SCRC50M1			SCRC100M1			SCRC20M3			SCRC50M3			SCRC100M3		
tv (45')	S-; 0; S+	34.5	24.7	22.6	40.0	35.2	31.9	47.4	45.3	42.2	42.1	42.1	40.5	35.0	28.1	21.7	32.9	34.1	18.1		32.9	23.9
	COV (%)	23.2			11.4			5.8			2.1			23.6			31.3					
	Rank	4			3			2			1			5			6			7		
PL (45')	S-; 0; S+	0.89	0.90	0.91	0.80	0.82	0.83	0.80	0.82	0.85	0.69	0.84	0.85	0.81	0.86	0.86	0.78	0.83	0.87		0.80	0.69
	COV (%)	1.1			1.9			3.1			11.3			3.4			5.5					
	Rank	1			2			3			6			4			5			7		
t500J (45')	S-; 0; S+	3.46	2.47	1.94	3.63	3.17	2.76	5.51	4.59	3.26	8.27	6.00	5.03	3.71	3.49	3.13	6.00	5.08	4.01		6.59	6.21
	COV (%)	29.4			13.7			25.4			25.8			8.5			19.8					
	Rank	6			2			4			5			1			3			7		
SFJ (45')	S-; 0; S+	715	790	795	700	745	765	640	690	740	600	630	680	695	725	750	655	680	710		620	610
	COV (%)	5.8			4.5			7.2			6.3			3.8			4.2					
	Rank	4			3			6			5			1			2			7		
PJ (45')	S-; 0; S+	27	10	10	28	15	10	30	23	20	34	26	22	24	20	17	25	21	17		24	30
	COV (%)	62.6			52.6			21.1			22.4			17.6			19.0					
	Rank	6			5			3			4			1			2			7		
t500 (90')	S-; 0; S+	3.71	2.44	1.93	5.12	2.8	2.36		5.83	4.13			9.05	6.42	4.44	2.78	8.93	7	4.44			
	COV (%)	34.0			43.3									40.1			33.2					
	Rank	2			4			5			6			3			1			7		
SF (90')	S-; 0; S+	695	715	760	560	690	700		640	645		455	485	550	660	695	515	570	585		435	
	COV (%)	4.4			12.0									11.9			6.9					
	Rank	1			4			5			6			3			2			7		
tv (90')	S-; 0; S+	41.5	34.5	34.1	66.6	48.8	42.0		61.8	52.0					65	36.1		70.3				
	COV (%)	11.3			24.2																	
	Rank	1			2			3			6			4			5			7		
PL (90')	S-; 0; S+	0.71	0.75	0.80	0.51	0.60	0.79		0.62	0.56		0.56	0.34	0.40	0.73	0.78	0.33	0.60	0.55		0.17	
	COV (%)	6.0			22.6									32.4			29.1					
	Rank	1			2			5			6			4			3			7		
t500J (90')	S-; 0; S+	4.66	3.12	2.88	8.00	4.83	3.76		7.44	5.57			18.8	10.9	7.69	5.76		12.4	5.87			
	COV (%)	27.2			39.9									32.3								
	Rank	1			3			4			6			2			5			7		
SFJ (90')	S-; 0; S+	670	720	730	575	660	680		590	675			510	510	600	690		530	605			
	COV (%)	4.5			8.7									15.0								
	Rank	1			2			5			6			3			4			7		
PJ (90')	S-; 0; S+	28	17	15	55	26	18		35	30			42	53	35	25		44	27			
	COV (%)	34.8			59.4									38.1								
	Rank	1			3			4			6			2			5			7		
SR_i		**74**			**109**			**117**			**151**			**91**			**123**			**203**		
Rrb		**1**			**3**			**4**			**6**			**2**			**5**			**7**		

Table VII-3. Test results and ranking of SCRCs according to COV of properties at different cement levels

		SCRC0			SCRC20M1			SCRC50M1			SCRC100M1		
τ_0 (15')	C-; 0; C+	70.6	79.0	83.2	88.6	90.0	96.7	92.6	114	130	97.4	132	150
	COV (%)	8.3			4.7			16.7			20.8		
	Rank	2			1			3			4		
μ_{pl} (15')	C-; 0; C+	25.5	30.8	31.2	30.7	31.8	33.0	31.9	33.0	35.5	36.2	57.9	59.0

		SCRC0			SCRC20M1			SCRC50M1			SCRC100M1		
	COV (%)	10.9			3.6			5.5			25.2		
	Rank	3			1			2			4		
τ_0 (45')	C-; 0; C+	214	214	244	228	251	310	240	297	347	293	361	386
	COV (%)	7.7			16.2			18.2			13.8		
	Rank	1			3			4			2		
μ_{pl} (45')	C-; 0; C+	28.8	32.8	38.1	33.0	33.0	41.5	34.3	36.5	44.4	52.2	63.7	67.3
	COV (%)	14.0			13.7			13.8			12.9		
	Rank	4			2			3			1		
τ_0 (90')	C-; 0; C+	504	515	608	596	644	744	659	846	1164	879	1079	3967
	COV (%)	10.6			11.4			28.7			87.5		
	Rank	1			2			3			4		
μ_{pl} (90')	C-; 0; C+	34.5	35.0	45.0	40.8	43.0	68.8	56.8	58.3	104	87.7	139	198
	COV (%)	15.7			30.6			36.6			39.0		
	Rank	1			2			3			4		
$f_{c,3d}$	C-; 0; C+	66.2	68.3	69.8	63.7	64.2	65.1	60.5	64.2	60.8	55.1	59.9	56.8
	COV (%)	2.7			1.1			3.3			4.3		
	Rank	2			1			3			4		
$f_{c,7d}$	C-; 0; C+	71.4	73.8	75.7	70.9	70.2	71.1	62.2	68.1	67.6	59.3	64.2	62.0
	COV (%)	2.9			0.7			5.0			3.9		
	Rank	2			1			4			3		
$f_{c,28d}$	C-; 0; C+	79.8	80.4	80.6	76.7	76.9	78.5	69.5	75.5	73.8	63.9	70.5	67.0
	COV (%)	0.5			1.3			4.3			4.9		
	Rank	1			2			4			3		
t500 (15')	C-; 0; C+	1.39	1.45	1.78	1.57	1.96	2.93	1.97	2.38	3.35	2.21	4.07	4.21
	COV (%)	13.6			32.5			27.6			31.9		
	Rank	1			3			2			4		
SF (15')	C-; 0; C+	820	815	760	800	745	705	790	710	685	760	680	660
	COV (%)	4.2			6.4			7.5			7.6		
	Rank	1			2			3			4		
tv (15')	C-; 0; C+	22.9	23.7	25.8	23.9	25.8	38.8	25.1	30.6	37.7	27.7	33.2	22.6
	COV (%)	6.2			27.6			20.4			19.0		
	Rank	1			4			3			2		
t500J (15')	C-; 0; C+	1.71	2.5	2.88	2.19	2.96	3.38	3.15	3.73	3.87	3.31	4.25	4.70
	COV (%)	25.3			21.2			10.7			17.3		
	Rank	4			3			1			2		
SFJ (15')	C-; 0; C+	820	820	740	775	750	720	740	700	695	715	675	680
	COV (%)	5.8			3.5			3.5			3.2		
	Rank	4			3			2			1		
PJ (15')	C-; 0; C+	9	10	19	12	13	20	15	19	21	16	20	22
	COV (%)	42.7			29.1			16.7			15.8		
	Rank	4			3			2			1		
SR	C-; 0; C+	16.0	13.6	12.1	16.4	13.1	11.3	13.1	11.5	8.8	8.2	3.5	3.9
	COV (%)	14.2			18.9			19.8			50.4		
	Rank	1			2			3			4		
t500 (45')	C-; 0; C+	1.71	1.95	2.23	2.33	2.31	2.52	2.47	2.75	3.77	2.62	5.41	5.75
	COV (%)	13.3			4.9			22.8			37.4		
	Rank	2			1			3			4		
SF (45')	C-; 0; C+	780	800	750	740	740	695	735	705	665	723	630	600

		SCRC0			SCRC20M1			SCRC50M1			SCRC100M1		
	COV (%)	3.2			3.6			5.0			9.9		
	Rank	1			2			3			4		
t500J (45')	C-; 0; C+	2.11	2.47	2.92	2.70	3.17	3.70	4.50	4.59	4.61	4.90	6.00	6.13
	COV (%)	16.2			15.7			1.3			11.9		
	Rank	4			3			1			2		
SFJ (45')	C-; 0; C+	800	790	730	755	745	715	695	690	685	675	630	640
	COV (%)	4.9			2.7			0.7			3.6		
	Rank	4			2			1			3		
PJ (45')	C-; 0; C+	10	10	20	13	15	21	19	23	24	20	26	27
	COV (%)	42.5			24.8			12.7			14.9		
	Rank	4			3			1			2		
t500 (90')	C-; 0; C+	2.32	2.44	2.99	2.64	2.8	4.95	3.18	5.83	6.03	5		
	COV (%)	13.8			37.2			31.7					
	Rank	1			3			2			4		
SF (90')	C-; 0; C+	730	715	680	690	690	650	680	640	570	580	455	
	COV (%)	3.6			3.4			8.8					
	Rank	2			1			3			4		
t500J (90')	C-; 0; C+	2.91	3.12	3.57	3.82	4.83	5.75	6.08	7.44	8.50	14.9		
	COV (%)	10.5			20.1			16.5					
	Rank	1			3			2			4		
SFJ (90')	C-; 0; C+	750	720	705	660	660	650	640	590	555	525		
	COV (%)	3.0			0.9			7.2					
	Rank	2			1			3			4		
PJ (90')	C-; 0; C+	16	17	20	20	26	28	33	35	46	38		
	COV (%)	12.3			17.2			18.4					
	Rank	1			2			3			4		
SR_i		**55**			**56**			**67**			**82**		
Rrb		**1**			**2**			**3**			**4**		

At this step, all properties are considered to evaluate robustness and then, for each mix, all the individual rankings have been summarized obtaining a "SR_i" value. This has been used to rank the mixes (within each material variation) according to their robustness, "Rrb" (from more robust to less robust). Moreover, the sum of rankings SR_i has been normalized according to Eq. 2. Table VII-1, Table VII-2 and Table VII-3 also show all these values for water, superplasticiser and cement variations, respectively.

Finally, according to the normalized sum of ranking, a category (high, medium-high, medium-low, low) that classifies the robustness has been selected (Table VII-4).

Table VII-4. SCRC robustness classification

Normalized sum of ranking	Robustness category
> 90%	High
60% to 90%	Medium-High
30% to 60%	Medium-Low
≤ 30%	Low

Then, Table VII-5 and Table VII-6 summarize the robustness category of the investigated mixes obtained with each of the three different material variations (water, superplasticiser and cement).

As seen in Table VII-5, when water and superplasticiser variations are analysed, the 20% replacement concretes (SCRC20M1 and SCRC20M3) show a medium-high level of robustness and SCRCs with a 50% of recycled aggregate display medium-high and medium-low robustness for M1 and M3 methods, respectively. Regarding the 100% replacement concretes, the M1 method provides a SCRC mix with a medium-low or low robustness whereas the M3 method always provide a concrete with a normalized sum of ranking ≤ 30%, which is considered as a low level of robustness. This mix will be, then, the least robust.

Table VII-5. Evaluation of SCRC robustness (water and superplasticiser variations)

Mix	Water variations		Superplasticiser variations	
	Normalized sum of ranking (%)	Robustness	Normalized sum of ranking (%)	Robustness
SCRC0	100	High	100	High
SCRC20M1	70	Medium-High	73	Medium-High
SCRC50M1	63	Medium-High	67	Medium-High
SCRC100M1	28	Low	40	Medium-Low
SCRC20M3	86	Medium-High	87	Medium-High
SCRC50M3	58	Medium-Low	62	Medium-High
SCRC100M3	0	Low	0	Low

When cement variations are observed (Table VII-6), these robustness categories are corroborated in general terms. As seen, the 20% replacement concrete shows a high level of robustness, the SCRC50M1 mix displays medium-low robustness and the 100% replacement percentage provides a concrete with a low robustness.

Table VII-6. Evaluation of SCRC robustness (cement variations)

Mix	Cement variations	
	Normalized sum of ranking (%)	Robustness
SCRC0	100	High
SCRC20M1	96	High
SCRC50M1	56	Medium-Low
SCRC100M1	0	Low

3.3 Selection of reliable SCRC properties to evaluate robustness

According to methodology, once the characteristic (robustness) has been assessed, it is necessary to be sure that there is agreement among the “judges” (properties) used. To check this, the Kendall’s coefficient has to be calculated and its significance measured. Table VII-7, Table VII-8 and Table VII-9 show the Kendall’s coefficient of concordance among concrete properties that were used as “judges” for water, superplasticiser and cement variations respectively.

Table VII-7. Kendall’s coefficient and Spearman’s $\rho_{s,j}$ (water variations)

SCRC	τ_0 (15’)	μ_{pl} (15’)	τ_0 (45’)	μ_{pl} (45’)	τ_0 (90’)	μ_{pl} (90’)	$f_{c,3d}$	$f_{c,7d}$	$f_{c,28d}$	t500 (15’)	SF (15’)	tv (15’)	PL (15’)	t500J (15’)	SFJ (15’)	PJ (15’)	SR	t500 (45’)	SF (45’)	tv (45’)	PL (45’)	t500J (45’)	SFJ (45’)	PJ (45’)	t500 (90’)	SF (90’)	tv (90’)	PL (90’)	t500J (90’)	SFJ (90’)	PJ (90’)	Rrb
	$R_{i,j}$																															
0	1	1	1	1	1	2	5	4	2	1	1	2	1	3	2	2	1	2	1	3	2	4	1	4	1	1	1	2	1	1	2	1
20M1	2	2	3	2	3	3	6	6	7	2	3	5	2	2	4	6	2	5	4	5	3	3	2	3	5	3	2	4	2	2	1	3
50M1	3	5	4	4	2	5	2	1	5	4	6	4	4	4	3	3	4	4	2	4	4	5	4	2	4	5	4	3	4	4	4	4
100M1	6	6	6	6	6	6	4	5	1	5	4	3	6	6	6	5	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
20M3	4	4	2	3	5	4	1	3	3	3	2	1	3	1	1	1	3	1	3	1	1	1	3	5	2	4	5	1	3	3	3	2
50M3	5	3	5	5	4	1	3	2	4	6	5	6	5	5	5	4	5	3	5	2	5	2	5	1	3	2	3	5	5	5	5	5
100M3	7	7	7	7	7	7	7	7	6	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
Kendall’s coefficient *W* (Eq. 5) = 0.6527																																
Spearman’s $\rho_{s,j}$ (Eq. 12)																																
$\rho_{s,j}$	0.9	0.8	1.0	1.0	0.8	0.6	0.3	0.3	0.2	0.9	0.9	0.7	1.0	0.9	0.9	0.8	1.0	0.8	0.9	0.7	1.0	0.6	1.0	0.3	0.9	0.8	0.8	0.9	1.0	1.0	0.9	

Table VII-8. Kendall’s coefficient and Spearman’s $\rho_{s,j}$ (superplasticiser variations)

SCRC	τ_0 (15’)	μ_{pl} (15’)	τ_0 (45’)	μ_{pl} (45’)	τ_0 (90’)	μ_{pl} (90’)	$f_{c,3d}$	$f_{c,7d}$	$f_{c,28d}$	t500 (15’)	SF (15’)	tv (15’)	PL (15’)	t500J (15’)	SFJ (15’)	PJ (15’)	SR	t500 (45’)	SF (45’)	tv (45’)	PL (45’)	t500J (45’)	SFJ (45’)	PJ (45’)	t500 (90’)	SF (90’)	tv (90’)	PL (90’)	t500J (90’)	SFJ (90’)	PJ (90’)	Rrb
	$R_{i,j}$																															
0	1	3	5	2	1	2	1	1	2	1	1	6	1	4	2	2	1	6	3	4	1	6	4	6	2	1	1	1	1	1	1	1
20M1	2	2	2	4	2	5	7	3	6	3	5	7	3	3	5	6	3	4	2	3	2	2	3	5	4	4	2	2	3	2	3	3
50M1	5	4	3	3	3	3	4	6	5	2	3	3	4	5	4	5	2	3	1	2	3	4	6	3	5	5	3	5	4	5	4	4
100M1	4	5	4	5	6	6	2	2	3	6	6	2	6	6	6	3	6	5	5	1	6	5	5	4	6	6	6	6	6	6	6	6
20M3	3	1	1	1	4	4	5	4	4	4	2	4	5	2	1	4	4	1	4	5	4	1	1	1	3	3	4	4	2	3	2	2
50M3	6	6	6	6	5	1	6	7	7	5	4	1	2	1	3	1	5	2	6	6	5	3	2	2	1	2	5	3	5	4	5	5
100M3	7	7	7	7	7	7	3	5	1	7	7	5	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
Kendall’s coefficient *W* (Eq. 5) = 0.4026																																
Spearman’s $\rho_{s,j}$ (Eq. 12)																																
$\rho_{s,j}$	0.9	0.9	0.6	0.9	0.9	0.5	0.0	0.4	-0.1	0.9	0.9	-0.5	0.7	0.5	0.8	0.3	0.9	0.3	0.6	0.1	0.9	0.4	0.6	0.2	0.6	0.8	0.9	0.8	1.0	0.9	1.0	

Table VII-9. Kendall’s coefficient and Spearman’s $\rho_{s,j}$ (cement variations)

SCRC	τ_0 (15’)	μ_{pl} (15’)	τ_0 (45’)	μ_{pl} (45’)	τ_0 (90’)	μ_{pl} (90’)	$f_{c,3d}$	$f_{c,7d}$	$f_{c,28d}$	t500 (15’)	SF (15’)	tv (15’)	t500J (15’)	SFJ (15’)	PJ (15’)	SR	t500 (45’)	SF (45’)	t500J (45’)	SFJ (45’)	PJ (45’)	t500 (90’)	SF (90’)	t500J (90’)	SFJ (90’)	PJ (90’)	Rrb
	$R_{i,j}$																										
0	2	3	1	4	1	1	2	2	1	1	1	1	4	4	4	1	2	1	4	4	4	1	2	1	2	1	1
20M1	1	1	3	2	2	2	1	1	2	3	2	4	3	3	3	2	1	2	3	2	3	3	1	3	1	2	2
50M1	3	2	4	3	3	3	3	4	4	2	3	3	1	2	2	3	3	3	1	1	1	2	3	2	3	3	3
100M1	4	4	2	1	4	4	4	3	3	4	4	2	2	1	1	4	4	4	2	3	2	4	4	4	4	4	4
Kendall’s coefficient *W* (Eq. 5) = 0.1402																											
Spearman’s $\rho_{s,j}$ (Eq. 12)																											
$\rho_{s,j}$	0.8	0.4	0.4	-0.8	1	1	0.8	0.6	0.8	0.8	1	0.2	-0.8	-1.0	-1.0	1	0.8	1	-0.8	-0.4	-0.8	0.8	0.8	0.8	0.8	1	

To evaluate the significance of Kendall's coefficient, a significance level (α) is chosen and then the critical value of *W* is determined (Table VII-10). When *W* equals or exceeds the critical value *W** obtained for a desired level of significance, it can be concluded that there is a good consensus among the properties used to evaluate robustness of the mixes.

Table VII-10. Critical values of Kendall's coefficient (*W)**

α	*W**	
	n = 7; k = 31	n = 4; k = 26
0.05	0.0615	0.0880
0.01	0.0805	0.1229

In both water and superplasticiser variations, as *W* is greater than the critical value *W**, for any of the considered significance levels, it can be concluded with considerable confidence that there is agreement among the 31 properties (k = 31) concerning the evaluation of the robustness of the mixes.

In the case of cement variations, the *W* value calculated given 26 properties (k = 26) is slightly higher than the critical values for the α = 0.05 and α = 0.01 significance levels. Then, the selected properties to "judge" robustness will be also in agreement for the considered significance levels.

Once the significance of Kendall's coefficient has been evaluated, the correlation between the rankings of an individual "judge" ($R_{i,j}$) and the final ranks of the objects, "Rrb", has to be assessed. To do so, Spearman's correlation test is used, being it then necessary to obtain Spearman's rank correlation coefficient.

In Table VII-7, Table VII-8 and Table VII-9, the Spearman's coefficient for each concrete property ($\rho_{s,j}$) is calculated, Eq. 12, for water, superplasticiser and cement variations respectively.

A positive result of this Spearman's $\rho_{s,j}$ implies a good correlation between the evaluation (ranking) obtained with this property and the final evaluation (rank) obtained in the mix when all studied properties are considered. A negative $\rho_{s,j}$ value indicates non correlation between the evaluation made with this property and the final evaluation obtained in the mix.

Therefore, those "judges" (properties) which provide no correlation have to be eliminated and those that provide low correlation can also be removed to simplify the robustness (characteristic) assessment. In this way, the number of properties ("judges") is changed and again, Kendall's coefficient has to be calculated and its significance checked according to the desired level of significance. Once this has been done, it can be concluded that the selection of properties that provide the best correlation to assess the robustness is achieved.

Then, some of the 31 properties that exhibited negative or low $\rho_{s,j}$ values were removed to reduce the number of properties that could be used for the evaluation of SCRC robustness. As a result, a minimum of six properties were selected: two rheological properties, τ_0 (15') and μ_{pl} (15'), and four workability parameters, t500 (15'), SF (15'), SFJ (15') and SR. This selection took into account the $\rho_{s,j}$ values obtained in the three material variations (water, superplasticiser and cement) (Table VII-7, Table VII-8 and Table VII-9). Moreover, these six properties would describe the rheological properties (fundamental physical quantities) and the three key workability characteristics (empirical physical quantities) of a SCRC mix.

The robustness categories determined using the six selected properties can be observed in Table VII-11, Table VII-12 and Table VII-13 for water, superplasticiser and cement variations, respectively. Both sets of properties, the full 31 and the 6 selected properties, showed the same results regarding robustness evaluation of the seven SCRC mixes (in general terms of high, medium-high, medium-low and low).

Table VII-11. Kendall's coefficient and Spearman's $\rho_{s,j}$ (6 properties - water variations)

SCRC	τ_0 (15')	μ_{pl} (15')	t500 (15')	SF (15')	SFJ (15')	SR	Rrb	Robustness
	$R_{i,j}$							
0	1	1	1	1	2	1	1	High
20M1	2	2	2	3	4	2	2	Medium-high
50M1	3	5	4	6	3	4	4	Medium-low
100M1	6	6	5	4	6	6	6	Low
20M3	4	4	3	2	1	3	3	Medium-high
50M3	5	3	6	5	5	5	5	Medium-low
100M3	7	7	7	7	7	7	7	Low
Kendall's coefficient (*W*) (Eq. 5) = 0.8433								
Spearman's $\rho_{s,j}$ (Eq. 12)								
ρ_s	0.96	0.89	0.96	0.82	0.82	1.00		

Table VII-12. Kendall's coefficient and Spearman's $\rho_{s,j}$ (6 properties - superplasticiser variations)

SCRC	τ_0 (15')	μ_{pl} (15')	t500 (15')	SF (15')	SFJ (15')	SR	Rrb	Robustness
	$R_{i,j}$							
0	1	3	1	1	2	1	1	High
20M1	2	2	3	5	5	3	3	Medium-high
50M1	5	4	2	3	4	2	4	Medium-high
100M1	4	5	6	6	6	6	6	Low
20M3	3	1	4	2	1	4	2	Medium-high
50M3	6	6	5	4	3	5	5	Medium-low
100M3	7	7	7	7	7	7	7	Low
Kendall's coefficient (*W*) (Eq. 5) = 0.7619								
Spearman's $\rho_{s,j}$ (Eq. 12)								
ρ_s	0.86	0.86	0.86	0.89	0.82	0.86		

Table VII-13. Kendall's coefficient and Spearman's $\rho_{s,j}$ (6 properties - cement variations)

SCRC	τ_0 (15')	μ_{pl} (15')	t500 (15')	SF (15')	SFJ (15')	SR	Rrb	Robustness
	$R_{i,j}$							
0	2	3	1	1	4	1	1	High
20M1	1	1	3	2	3	2	2	High
50M1	3	2	2	3	2	3	3	Medium-high
100M1	4	4	4	4	1	4	4	Low
Kendall's coefficient (*W*) (Eq. 5) = 0.3000								
Spearman's $\rho_{s,j}$ (Eq. 12)								
ρ_s	0.80	0.40	0.80	1.00	-1	1		

Again, to determine the significance of *W*, a significance level (α) has to be chosen and the critical value of *W* for this α obtained (Table VII-14) [KEND90]. If the calculated *W* (Table VII-11, Table VII-12 and Table VII-13) is greater than or equal to the critical value of the Kendall's coefficient *W** for any particular level of significance, Table VII-14, then there is a good agreement among the properties used to evaluate robustness.

Table VII-14. Critical values of Kendall's coefficient (*W)**

α	W^*	
	n = 7, k = 6	n = 4, k = 6
0.05	0.2589	0.3276
0.01	0.3351	0.4505

As it can be seen, in both water and superplasticiser variations, W exceeds the critical value W^* for all the considered significance levels. So, it can be concluded with considerable confidence that there is a high agreement among the selected 6 properties (k = 6) when water or superplasticiser vary.

The $\rho_{s,j}$ values were recalculated with the final ranking (Rrb) obtained for each mix (according to the sum of rankings obtained with the six selected properties). They are presented in Table VII-11, Table VII-12 and Table VII-13. According to these $\rho_{s,j}$, it can be concluded that τ_0 (15 min), μ_{pl} (15 min), t500 (15 min), SF (15 min), SFJ (15 min) and SR can be successfully used to assess the SCRC robustness due to the fact that all of them suitably correlate with the final result obtained.

In the case of cement variations, the W value calculated with the six selected properties was lower than the critical value W^* for both α = 0.05 and α = 0.01 significance levels. As seen when 26 properties were considered, cement variations are less sensitive to evaluate robustness than water and superplasticiser ones (it would be necessary to make more tests to evaluate the SCRC robustness).

Lastly, it can be seen that when water variations are imposed the values of Kendall's coefficient and Spearman's coefficient are the highest ones. Therefore, according to the results of this statistical approach and in agreement with the analysis of the sensitivity parameters, introducing water variations in the mix is the most effective procedure to asses SCRC robustness.

4 CONCLUSIONS

In this chapter, the robustness of self-compacting recycled concrete (SCRC) was deeply analysed. Based on the results obtained, the following conclusions can be drawn:

- The conclusion obtained with the sensitivity parameters and with the statistical approach leads to state that water is the key factor that affects SCRC robustness. Moreover, the statistical approach based on Kendall's coefficient of concordance and Spearman's rank correlation was successfully used to identify key properties of SCRC that can be measured to evaluate robustness: τ_0 (15 min), μ_{pl} (15 min), t500 (15 min), SF (15 min), SFJ (15 min) and SR.
- SCRC is less robust than SCC. This is due to the fact that SCRC presents the "rheological parameter – $(w/c)_{ef}$" and "rheological parameter – $\varnothing/\varnothing_{max}$" curves with higher slope than the ones of conventional SCC. Then, when high percentages of recycled coarse aggregate are used, there is a greater possibility to reach the high slope region of high slope curves causing high yield stress changes (and similarly high plastic viscosity changes and high empirical parameters changes). Additionally, the use of aggregates with a moisture content makes it more difficult to design robust SCRCs, as it occurs with SCCs.

Hence, lastly, SCRC robustness will depend on the quantity of water compensated in the mixing protocol and on the region of the "rheological parameter - $(w/c)_{ef}$" curve where the concrete has been designed (near or far from the high slope).

CHAPTER VIII
Thixotropy of self-compacting recycled concrete

1 INTRODUCTION AND OBJECTIVES

1.1 Introduction

Thixotropy is by definition a time-dependent, isothermal and reversible process [BILL11]. When a cementitious suspension is sheared, its network structure is broken into smaller agglomerates and, with continued shearing, eventually there is an equilibrium state in which the agglomerates cannot be broken down into smaller fragments. When the suspension is at rest, the particles can form weak physical bonds and agglomerate into a network [FERR07].

In this way, when a fresh concrete is subjected to deformation (shearing), thixotropy describes the reversible and time-dependent reduction of its viscosity, which is caused by the build-up of a structure in fresh concrete at rest. This structure, which provides an initial resistance to deformation, is destroyed once sufficient deformation is applied to the concrete [KOEH07]. This means that the physical structure building up with time in the material at rest can be broken down and that the steady-state rheology characterising the material before rest can be regained [BILL11]. In the absence of shear during rest, the damaged structure rebuilds. The physical origin of this rebuilding might find its foundations in the Brownian motion that could induce a slow rearrangement of the particle configuration or in an evolution of the colloidal interactions between particles [RAHM14].

For cementitious materials, however, an irreversible chemical reaction is also under way from the moment the cement is intermixed with water. In practical terms, this appears as a loss in slump over time [BILL11]. Then, the structural build-up phase of cementitious materials is a function of both the reversible structural changes from the thixotropic phenomena and the irreversible structural changes due to hydration mechanisms and the resulting microstructure [FERR07]. The thixotropic properties of cement pastes that are measured macroscopically are strongly dependent on microstructural considerations [ASSA04].

The apparent viscosity of the material is permanently evolving. Over short timescales, flocculation and de-flocculation processes dominate, which lead to rapid thixotropic (reversible) effects, while over larger timescales, hydration processes dominate, which lead to irreversible evolutions of the behaviour of the fluid. These two effects might in fact act at any time. As a consequence of this, it is reasonable to consider that there is an intermediate period, at about a couple thousand seconds, in which irreversible effects have not yet become significant. This means that it seems possible to model thixotropy and only thixotropy during short periods of time (not more than 30 min as an order of magnitude) during which the irreversible evolutions of the concrete can be neglected [ROUS06a].

Thixotropy is strongly dependent on the composition of the mixture: cement characteristics, chemical admixtures, supplementary cementitious materials and water to cement (w/c) ratio are parameters that affect the thixotropic phenomenon. Also, external parameters such as mixing and vibration influence thixotropy [ASSA04].

The total amount of powders in the mixture, as the particles contained in these various powders are the only particles at the origin of thixotropy in SCC [RAHM14]. It is believed that thixotropy should increase when powder content increases.

The weight ratio between water and powders affects the average distance between cement (or other alternative powders) particles and thus their mutual interactions. Thixotropy should increase when water to powder ratio decreases. It should also increase with the specific surface of the powders. The fineness of powders affects the structuration rate as the amplitudes of Brownian and colloidal effects increase when particle size decreases. Then, a lower water to cement ratio and a higher content of powder (i.e. content of fines) implies a higher degree of thixotropy.

Regarding coarse aggregates, their effect in thixotropy will be more related to their volume concentration, i.e. the amount of granular skeleton (sand and gravel) in mixture. In fact, both the sand-to-total aggregate ratio and the volumetric ratio of the paste-to-coarse aggregate were found to affect thixotropy due to the increase of the degree of internal friction resulting from greater coarse aggregate content. The aggregate-to-aggregate contact, that induces greater degree of internal friction within the mixture, will increase the shear stresses necessary to break down the material. The decrease of paste volume or increase of coarse aggregate volume can lead to higher thixotropy.

Moreover, Mahaut et al. [MAHA08] considered (Eq. 1) that if the mechanical impact of the coarse particles is to increase the yield stress by a factor f(Ø), then their impact on the structuration rate of the paste is to also increase it by a factor f(Ø). It is thus sufficient to measure the cement paste yield stress evolution in time (i.e. A_{thix}) and to measure the increase of the yield stress with the volume fraction (i.e. f(Ø)) for a single resting time to infer the A_{thix}·f(Ø) value of the structuration rate of the suspension (and more generally of fresh concrete).

$$\tau_c\,(\emptyset,t)=\tau_c\,(0)\cdot f(\emptyset)+A_{thix}\cdot f(\emptyset)\cdot t \tag{1}$$

These authors concluded that it is sufficient to know how the interstitial cement paste evolves in time to predict the suspension evolution at rest (suspension of coarse particles in a cement paste). This is important for fresh concrete as its behaviour is hard to measure. Their results showed that the knowledge of the cement paste structuration rate at rest (A_{thix}) is sufficient to predict the fresh concrete structuration rate.

Lastly, it can be concluded that thixotropy is of particular interest to users of SCC, as it may provide another link into predicting its flow behaviour [FERR07]. The rheological behaviour of concrete is related to this network structure and the rate at which it can form. Thixotropy, which is manifested in the difference between static and dynamic yield stress or in the breakdown area between upward and downward rheometer flow curves, contributes by increasing segregation resistance and reducing formwork pressures. Too much thixotropy, however, reduces placeability and can affect interlayer bond strength [KOEH07].

1.2 Objectives

As already mentioned in Chapter III, in the third phase of this work, named **"Thixotropy"**, several testing methods and protocols were used to evaluate the degree of thixotropy of self-compacting recycled concrete (SCRC). Furthermore, the structural build-up developed after a certain period of rest (due to thixotropy) can affect interlayer bond strength in SCRC.

Therefore, in this phase, the first objective is to analyse the degree of thixotropy developed in SCRC mixes according to the following methods: structural breakdown curves at various rotational speeds (steady state approach), hysteresis loop flow curves and yield stress at rest (also referred to as static yield stress and shear-growth yield stress). Lastly, the second objective is to evaluate the effect of the structural build-up at rest on interlayer bond strength throughout the following two methods: interlayer bond strength using flexural tests and interlayer bond strength using water permeability tests.

As described in Chapter III, four SCRC mixes with 0%, 20%, 50%, and 100% of recycled coarse aggregate (% RCA) were evaluated. Three batches for each SCRC mix were made. In the first one, the four structural breakdown tests were carried out. In the second batch, the hysteresis loop test was conducted and the specimens to carry out bond strength under flexure tests were made. In the third batch, the protocol adopted for the determination of yield stress at rest was executed and the specimens to develop water permeability tests were fabricated. Figure VIII-1 summarizes this program.

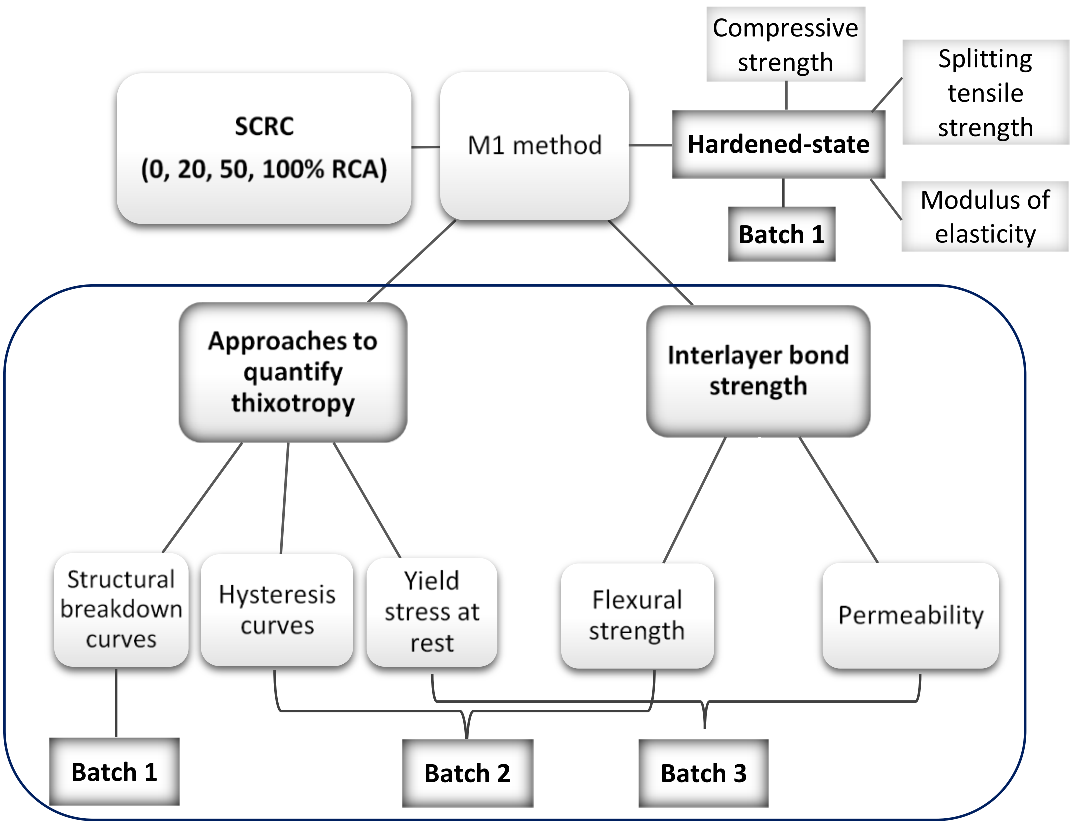


Figure VIII-1. Thixotropy analysis flow-chart

2 ASSESSMENT OF SCRC THIXOTROPY

2.1 Structural breakdown curves

As indicated in Chapter III, the concrete was subjected to different constant rotational speeds of 0.3, 0.5, 0.7 and 0.9 rps. The time elapsed between each test (developed at each of these speeds) was approximately 8 min. During the first 3 min, the concrete was rehomogenized to avoid any kind of orientation, and the last 5 min the concrete remained at rest in the rheometer bowl.

At each rotational speed, a structural breakdown curve was determined (torque versus time). Each curve shows a peak yield stress value (τ_i) that corresponds to the initial structural build-up condition after a given rest period (of 5 min, according to the described procedure). After this peak, the shear stress decays with time towards an equilibrium value (τ_e) that is independent of the shear history, for that speed.

The evaluation of thixotropy with the structural breakdown curves can be made analysing two indices. The first is the difference between the peak shear stress (τ_i) and the shear stress at equilibrium (τ_e), for any given rotational speed. This provides a measurement of the amplitude of the structural modifications inside the tested concrete. Second, peak and equilibrium shear stresses obtained at each speed can be used to draw a graphic "shear stress (τ) versus speed (N)" with an "initial flow curve (τ_i(N))" and an "equilibrium flow curve (τ_e(N))". The enclosed area between the initial flow curve (τ_i(N)) and the equilibrium flow curve (τ_e(N)) quantifies the thixotropic phenomenon. This area, known as the "breakdown area (A_b)" (Eq. 2), provides a measurement of the energy required per unit time and unit volume to break the structural build-up developed.

Breakdown area (A_b) = $\int_{0.3}^{0.9} (\tau_i(N) - \tau_e(N))\, dN$ (2)

A greater difference between shear stress initially and at equilibrium ($\tau_i - \tau_e$) implies a higher degree of thixotropy. A greater "breakdown area (A_b)" implies a higher energy necessary to break the initial linkages and internal friction to pass from the initial state into a state of equilibrium.

Figure VIII-2, Figure VIII-3, Figure VIII-4 and Figure VIII-5 show the structural breakdown curves for each SCRC mix. From these figures, it can be deduced that the shearing action induces a considerable amount of breakdown in SCRC mixes in just a few seconds, as it occurs in conventional SCC [ASSA04]. This breakdown increases with rotational speed.

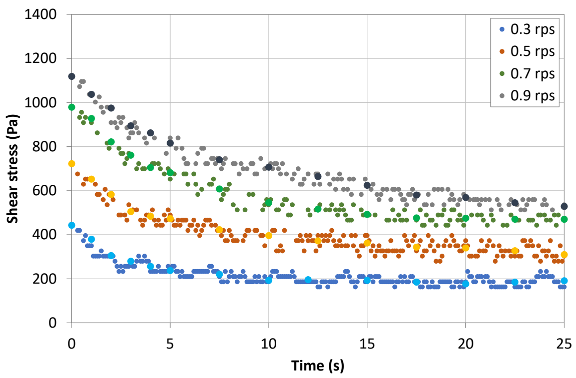


Figure VIII-2. Structural breakdown curves for SCRC0 mix

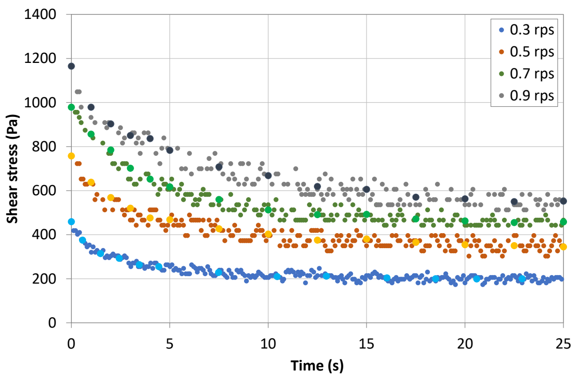


Figure VIII-3. Structural breakdown curves for SCRC20 mix

A similar behaviour can be appreciated between the reference SCC and the 20% replacement concrete (Figure VIII-2 and Figure VIII-3), i.e. their structural breakdown curves are similar. In the case of 50% of recycled aggregate, a slight increase in the values of shear stress can be seen (Figure VIII-4). The 100% replacement concrete shows this increasing tendency more clearly (Figure VIII-5).

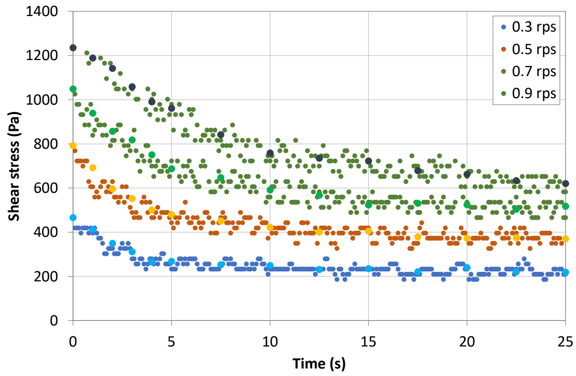


Figure VIII-4. Structural breakdown curves for SCRC50 mix

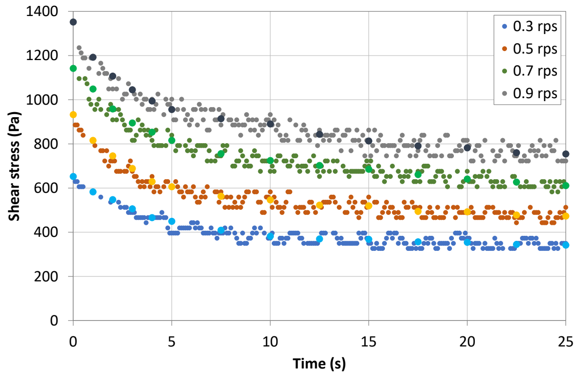


Figure VIII-5. Structural breakdown curves for SCRC100 mix

The results determined during the four series of measurements are given in Table VIII-1.

Regarding τ_i and τ_e values, at a rotational speed of 0.3 rps, the τ_i value increased from 442.88 to 652.66 Pa for mixes made with % RCA values of 0 and 100% respectively. For the τ_e values, such increase corresponded to 188.30 and 345.08 Pa respectively.

At a rotational speed of 0.5 rps, the τ_i value increased from 722.59 to 932.37 Pa for mixes made with % RCA values of 0 and 100% respectively. For the τ_e values, such increase corresponded to 324.87 and 477.59 Pa respectively.

Table VIII-1. Thixotropic indices (structural breakdown test)

		SCRC0		
	0.3 rps	0.5 rps	0.7 rps	0.9 rps
τ_i (Pa)	442.88	722.59	978.99	1118.85
τ_e (Pa)	188.30	324.87	470.67	543.88
$\tau_i - \tau_e$	254.58	397.72	508.32	574.96
A_b = 260.35 J/m^3·s				
		SCRC20		
	0.3 rps	0.5 rps	0.7 rps	0.9 rps
τ_i (Pa)	459.23	757.55	978.99	1165.47
τ_e (Pa)	200.00	348.15	455.59	559.42
$\tau_i - \tau_e$	259.23	409.40	523.40	606.05
A_b = 269.72 J/m^3·s				
		SCRC50		
	0.3 rps	0.5 rps	0.7 rps	0.9 rps
τ_i (Pa)	466.19	792.52	1048.92	1235.40
τ_e (Pa)	220.30	374.81	507.95	630.49
$\tau_i - \tau_e$	245.89	417.71	540.97	604.91
A_b = 271.42 J/m^3·s				
		SCRC100		
	0.3 rps	0.5 rps	0.7 rps	0.9 rps
τ_i (Pa)	652.66	932.37	1142.16	1351.94
τ_e (Pa)	345.08	477.59	606.04	745.90
$\tau_i - \tau_e$	307.58	454.78	536.12	606.04
A_b = 285.68 J/m^3·s				

At a rotational speed of 0.7 rps, the τ_i value increased from 978.99 to 1142.16 Pa for mixes made with % RCA values of 0 and 100% respectively. For the τ_e values, such increase corresponded to 470.67 and 606.04 Pa respectively.

At a rotational speed of 0.9 rps, the τ_i value increased from 1118.85 to 1351.94 Pa for mixes made with % RCA values of 0 and 100% respectively. For the τ_e values, such increase corresponded to 543.88 and 745.90 Pa respectively.

In Figure VIII-6, the variations of τ_i and τ_e with the increase in rotational speed are plotted for the four SCRC mixes. It can be noted that the incorporation of high replacement percentages contributes to increase the τ_i and τ_e values. Moreover, the difference between the τ_i and τ_e values, that offers a measurement of the degree of thixotropy, shows a slight increase with the percentage of recycled coarse aggregate at any rotational speed.

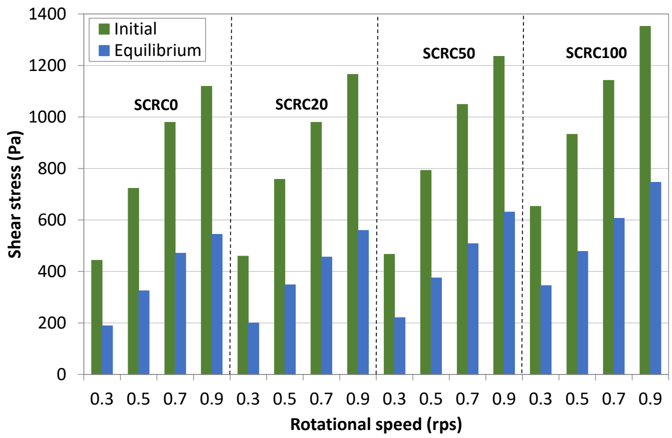


Figure VIII-6. τ_i and τ_e at each rotational speed for each SCRC. Structural breakdown curves

The τ_i vs. N and τ_e vs. N plots for each SCRC mix are reported in Figure VIII-7, Figure VIII-8, Figure VIII-9 and Figure VIII-10. These figures show the A_b value considered between the initial flow curve (τ_i vs. N) and the equilibrium flow curve (τ_e vs. N) for each concrete.

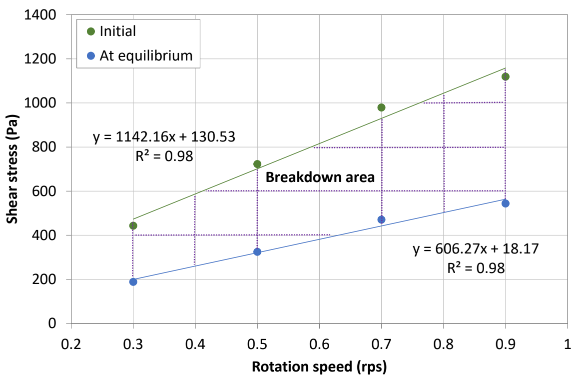


Figure VIII-7. Breakdown area of SCRC0 mix

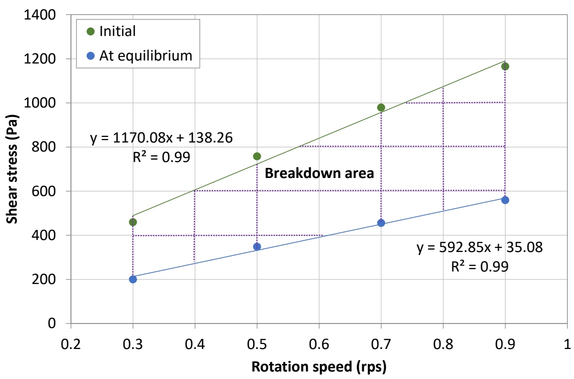


Figure VIII-8. Breakdown area of SCRC20 mix

Regarding the "breakdown area", the A_b values show a slight increase with the increase in the percentage of recycled coarse aggregate. Such increase was from 260.35 to 285.68 J/m³·s for mixes made with % RCA values of 0 and 100% respectively.

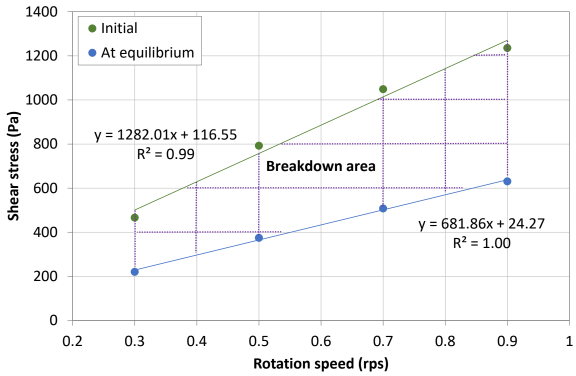


Figure VIII-9. Breakdown area of SCRC50 mix

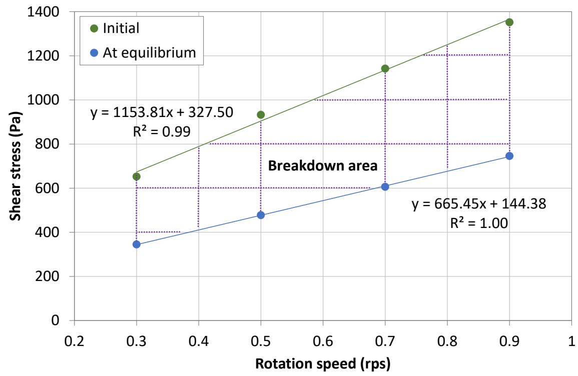


Figure VIII-10. Breakdown area of SCRC100 mix

Therefore, compared to the reference mix (SCRC0), the results indicate that concrete made with recycled aggregates resulted in slightly higher thixotropic indices, as indicated by the increase in ($\tau_i - \tau_e$) and A_b (Figure VIII-11).

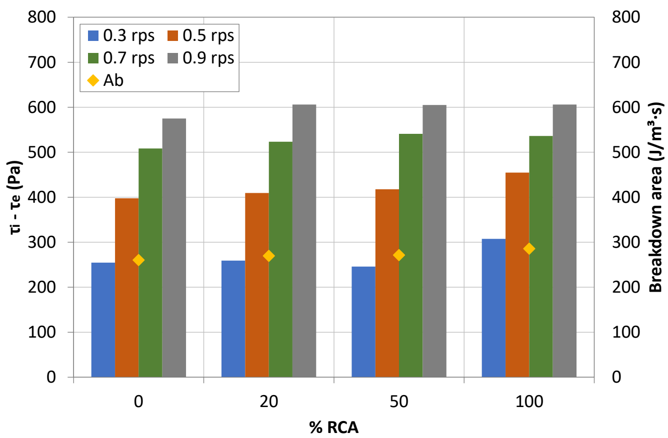


Figure VIII-11. "(τ_i - τ_e) vs. % RCA" and "Breakdown area vs. % RCA"

2.2 Hysteresis curves

As already described in Chapter III, the concrete was sheared with a continuously increasing shear rate and continuously down again to zero shear rate. The rotational speed was applied for 60 s from 0 to 0.5 rps and then from 0.5 rps to 0.

This rheological test was carried out at 15, 30, 45 and 75 min since the cement-water contact (that corresponds to 5, 15, 15 and 30 min resting time). Two measurements at 15 min were developed to better verify the results. For a given resting period, the enclosed area between the up-curve of each hysteresis loop and the corresponding equilibrium line was used to evaluate the rebuilding that occurred in the mix. This area (A_h) has the physical dimension of energy per unit time and unit volume. A greater hysteresis loop area implies a higher degree of thixotropy.

It is explained that hysteresis loops normally measure transient flow properties somewhere between the peak and equilibrium stresses for a given shear rate [ASSA04]. Conversely, the previous structural breakdown approach enables measuring the entire shear stress range as a function of time for any given shear rate.

Hysteresis loops are said to have a number of bad points. Firstly, a loop test is often carried out too quickly. Secondly, a test where both shear rate and time are changed simultaneously on a material where the response is itself a function of both shear rate and time is a bad experimentation [BARN97, ASSA04]. However, the use of the hysteresis loop test can be useful to evaluate the structural build-up of cement-based materials as long as it is carefully run and interpreted [FERR07].

Table VIII-2 shows the results of "hysteresis area (A_h)" for each SCRC mix at each resting time.

Table VIII-2. Hysteresis area (hysteresis curves test)

Mix	Index	Resting time			
		5 min	15 min	15 min	30 min
SCRC0	A_h (J/m^3·s)	41.0	111.5	113.8	152.9
SCRC20	A_h (J/m^3·s)	50.2	114.2	117.3	157.1
SCRC50	A_h (J/m^3·s)	48.9	121.5	128.8	157.7
SCRC100	A_h (J/m^3·s)	57.8	120.8	139.8	165.5

The A_h values are shown to be quite similar, with a slight increasing tendency when the percentage of recycled coarse aggregate increases (Figure VIII-12). Such increase was from 41.0 to 57.8 J/m^{3}s at 5 min resting time for mixes made with % RCA values of 0 and 100% respectively. The same increase was from 111.5 to 120.8 J/m^{3}s, from 113.8 to 139.8 J/m^{3}s and from 152.9 to 165.5 J/m^{3}s at 15, 15 and 30 min respectively.

Finally, Figure VIII-13 shows the change in thixotropy (measured with the hysteresis areas) with the elapsed time. It can be seen that all concretes show a similar trend.

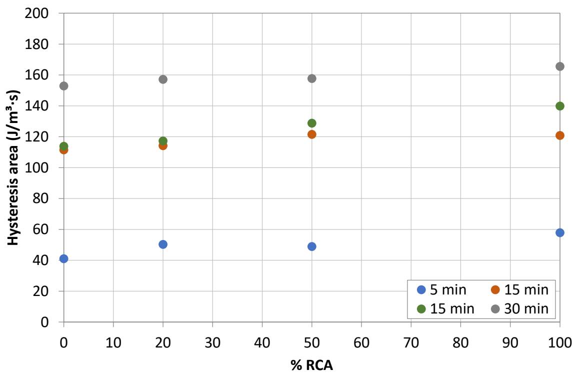


Figure VIII-12. Hysteresis area vs. % RCA

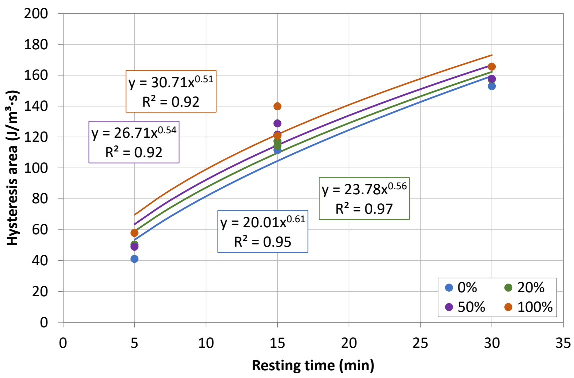


Figure VIII-13. Hysteresis area vs. Resting time

2.3 Yield stress at rest

As indicated earlier, a low and constant rotational speed of 0.03 rps for 60 s (time enough to measure the maximum torque and to reach the steady state region) was applied to the vane immersed in the fresh concrete. This protocol was carried out at 15, 30, 45 and 75 min since the cement-water contact (again 5, 15, 15 and 30 min resting time). Before conducting the first test, the SCRC was placed in the bowl of the rheometer and allowed to rest for 5 min. After each test, the vane was removed, concrete remixed with a shovel and left to rest until the next testing time.

Figure VIII-14, Figure VIII-15, Figure VIII-16 and Figure VIII-17 show the shear stress-time profiles for each SCRC mix.

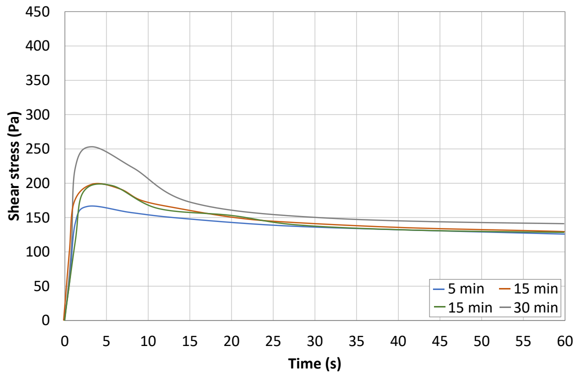


Figure VIII-14. Shear stress-time for SCRC0 mix

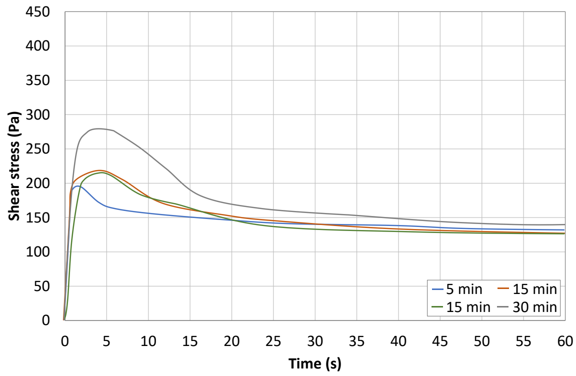


Figure VIII-15. Shear stress-time for SCRC20 mix

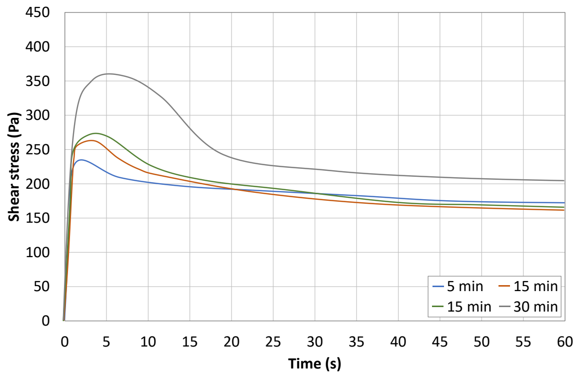


Figure VIII-16. Shear stress-time for SCRC50 mix

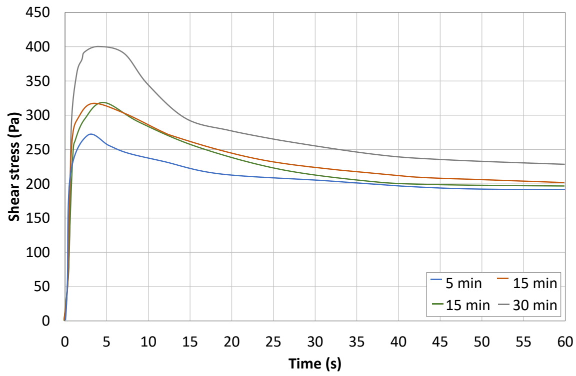


Figure VIII-17. Shear stress-time for SCRC100 mix

The evaluation of thixotropy with this test can be made analysing two indices. The first one is the value of yield stress at rest (τ_0). The yield stress at rest is an index of thixotropy since when reached, the majority of the bonds are broken allowing the flow of the material. The second one is, again, the difference between the peak shear stress (in this test, τ_0) and the shear stress at equilibrium (τ_e). As aforementioned, this provides a measurement of the amplitude of the structural modifications inside the tested concrete. A greater difference between both values implies a higher degree of thixotropy.

Table VIII-3 and Figure VIII-18 summarize the yield stress at rest (τ_0) and shear stress at equilibrium (τ_e) values for the SCRC mixes.

Table VIII-3. Thixotropic indices (Yield stress at rest test)

Mix	Index	Resting time			
		5 min	15 min	15 min	30 min
SCRC0	τ_0 (Pa)	163.17	195.80	195.80	252.91
	τ_e (Pa)	122.37	130.53	122.37	138.69
	$(\tau_0 - \tau_e)$ (Pa)	40.79	65.27	73.42	114.22
SCRC20	τ_0 (Pa)	188.81	220.39	212.23	279.71
	τ_e (Pa)	130.53	125.87	125.87	139.86
	$(\tau_0 - \tau_e)$ (Pa)	58.27	94.52	86.36	139.86
SCRC50	τ_0 (Pa)	235.42	261.06	277.38	358.96
	τ_e (Pa)	171.32	163.17	163.17	205.12
	$(\tau_0 - \tau_e)$ (Pa)	64.10	97.90	114.22	153.84
SCRC100	τ_0 (Pa)	269.36	318.34	318.41	399.99
	τ_e (Pa)	190.67	203.96	195.80	228.43
	$(\tau_0 - \tau_e)$ (Pa)	78.69	114.38	122.61	171.56

The longer the concrete is maintained at rest, the more the thixotropic structural build-up becomes significant requiring higher initial yield stress to breakdown the structure. The histogram plotted in Figure VIII-18 clearly shows this tendency. Due to the fact that the speed is kept at 0.03 rps, the equilibrium shear stress is similar for each concrete at any time.

When the replacement percentage moves from 0% to 100%, the τ_0 value increases from 163.17 to 269.36 Pa, from 195.80 to 318.34 Pa, from 195.80 to 318.41 Pa and from 252.91 to 399.99 Pa at 5, 15, 15 and 30 min resting time, respectively.

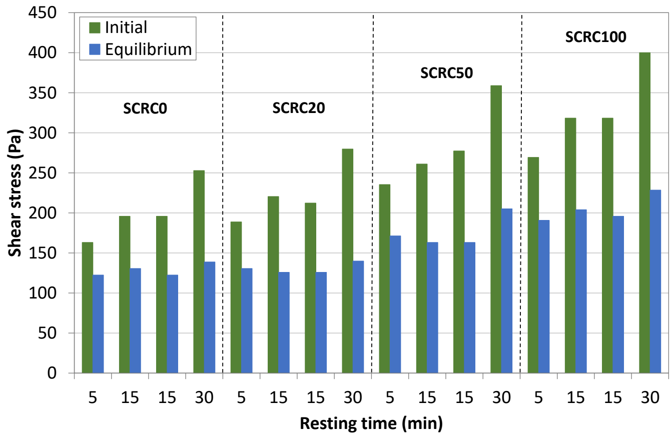


Figure VIII-18. τ_i and τ_e at each resting time for each SCRC. Yield stress at rest

Figure VIII-19 shows the ($\tau_0 - \tau_e$) index. In parallel with τ_0, this index increases from 40.79 to 78.69 Pa, from 65.27 to 114.38 Pa, 73.42 to 122.61 Pa and from 114.22 to 171.56 Pa at 5, 15, 15 and 30 min resting time, respectively.

As in the previous sub-sections, compared to the reference mix (SCRC0), the results indicate that concrete made with recycled aggregates resulted in slightly higher thixotropic indices.

Finally, again, Figure VIII-20 shows the change in thixotropy (measured with yield stress at rest test) with the elapsed time. It can be seen that, in agreement with the results obtained with the hysteresis curves test, all concretes show a similar trend.

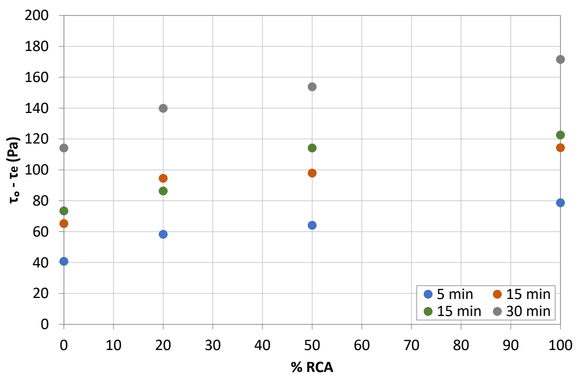


Figure VIII-19. $\tau_0 - \tau_e$ vs. % RCA

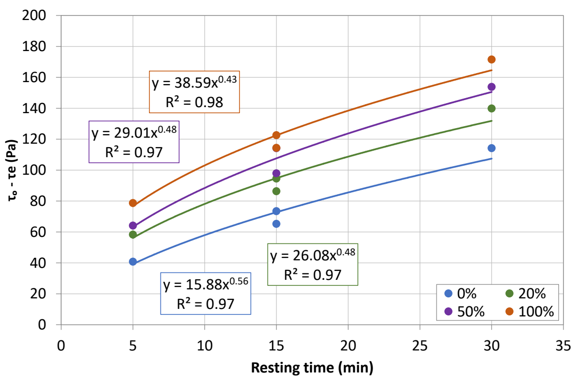


Figure VIII-20. $\tau_0 - \tau_e$ vs. Resting time

As thixotropy depends on the paste composition, and the paste composition of all concretes is similar, small differences in all SCRC mixes are found when analysing any of the indices used to measure this property. Only a slight increase with the replacement percentage can be observed. This increase is due to the difference in the effective w/c ratio of the self-compacting recycled concretes, as a result of the non–compensated water absorption. Moreover, the incorporation of recycled coarse aggregate introduces a higher amount of fines from the crushing of the adhered mortar. These fines can present hydraulic activity and then contribute to change the paste composition, decreasing, also, the effective w/c ratio of SCRC. Both these effects are, obviously, more significant in concretes with high replacement percentage.

Moreover, according to Chapter VI, the behaviour over time of the SCRC depends on the quantity of water compensated in the mixing protocol. This and the region of the "rheological variations – $(w/c)_{ef}$" curves where the concrete has been initially designed control SCRC fresh behaviour over time and therefore, the thixotropic changing rate. In this case, due to the effective w/c ratio designed in this phase (0.49), changes in this ratio over time are taking place on the slight slope region of the "rheological variations – $(w/c)_{ef}$" curves. Therefore, the thixotropic changing rate is very similar in all studied mixes.

In conclusion, thixotropy of the studied SCRCs is slightly higher when high replacement percentages are used, showing all concretes a similar thixotropic changing rate. Therefore, it is expected that SCRCs hardly show differences in their interlayer bond strength when compared with the baseline SCC.

3 INTERLAYER BOND STRENGTH OF SCRC

This section is focused on the second objective of the third working phase: the evaluation of the interlayer bond strength of SCRC and the assessment of the influence of thixotropy on this property.

During placing, a layer of a self-compacting concrete has a short time to rest and flocculate before a second layer of concrete is cast on it. If it flocculates too much and its apparent yield stress increases above a critical value, then the two layers may not intermix properly and, as vibrating is not allowed in the case of SCC, this creates a weak interface in the final structure [ROUS06a].

A highly thixotropic SCC mix (high level of structural build-up at rest) can show a low interlayer bond strength depending on the delay time between layers. The resulting bond associated with multi-layer casting can decrease with the increase in waiting period between successive castings, which will result in an increase in static yield stress (and viscosity) of the concrete cast in the lower lift [KHAY12a].

Then, a low interlayer bond strength is related to a high thixotropy. This means that if the thixotropy of a mix is high enough, then its interlayer bond strength will be lower than if the mix is less thixotropic.

In this work, the evaluation of the interlayer bond strength of SCRC is made using flexure and water permeability tests. Specimens are cast using two layers, being the delay time between them of 0, 15, 30 and 60 min (15, 30, 45 and 75 min since the cement-water contact, respectively).

As mentioned in Chapter III, for each type of SCRC (0%, 20%, 50% and 100% of recycled coarse aggregate), 2 reference small beams (600 mm x 100 mm x 100 mm) were cast in one layer, and another 7 beams were cast in two layers considering the interface between them at mid-span. Each beam was subjected to a three-point bending test. Table VIII-4 and Figure VIII-21 show the results obtained on these flexure tests.

The residual bond under flexure stress with delay time is also shown in Table VIII-4 and plotted in Figure VIII-22. This residual flexural strength between two layers at a certain delay time was calculated by dividing flexural strength of specimen of the same delay time, $f_{cf\ (delay\ time)}$, by flexural strength of reference specimen, $f_{cf\ (zero\ time)}$.

Table VIII-4. Evaluation of interlayer bond strength using flexure tests

Mix	Flexural strength (MPa)			
	Delay time			
	0 min	15 min	30 min	60 min
SCRC0	3.9	4.0	4.0	3.8
SCRC20	4.0	4.3	4.4	3.9
SCRC50	3.9	3.8	4.2	3.9
SCRC100	3.7	3.6	3.5	3.3
	Residual flexural strength ($f_{cf\,(delay\,time)}/f_{cf\,(zero\,time)}$)			
Mix	Delay time			
	0 min	15 min	30 min	60 min
SCRC0	1.00	1.03	1.03	0.97
SCRC20	1.00	1.08	1.10	0.98
SCRC50	1.00	0.97	1.08	1.00
SCRC100	1.00	0.97	0.95	0.89

Khayat et al. [KHAY12a] found that the residual flexural strength for a delay time of 15 min of SCC with low thixotropy can be very high (around 95%). However, for a delay time of 60 min, the residual flexural strength of SCC with a high thixotropy degree can decrease considerably (around 50%). Keeping this statement in mind, the studied concretes show a low thixotropy level.

Moreover, the residual flexural strength is similar in all concretes at any time, although it can be noted that for the total replacement percentage, the decrease in flexural strength is a little more noticeable. This is due to the thixotropy that is slightly higher when high replacement percentages are used.

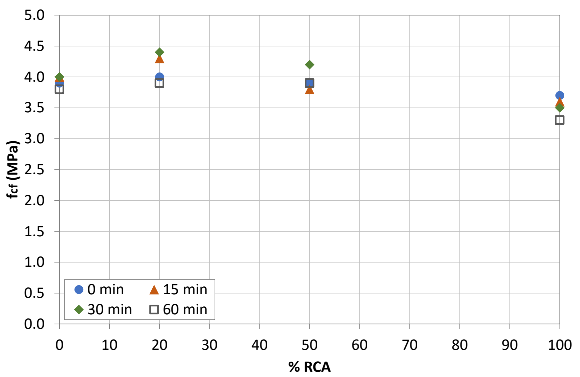


Figure VIII-21. Flexural strength at each delay time vs. % RCA

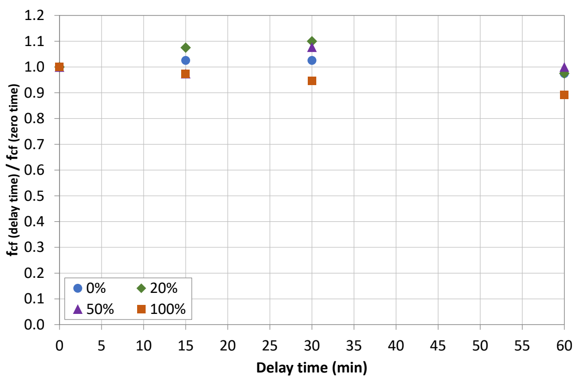


Figure VIII-22. Residual flexural strength for each % RCA vs. Delay time

Regarding water permeability tests, six prismatic specimens (200 mm x 100 mm x 100 mm) of each SCRC mix were used for the maximum water penetration under pressure test. In this test, a water column acts on the specimen 72 h under 5 bars of pressure, equivalent to keep the specimens 50 m depth under water.

Table VIII-5 summarizes the results obtained regarding the water penetration depth for each SCRC mix and taking into account the aforementioned delay times between successive layers.

Table VIII-5. Evaluation of interlayer bond strength using water permeability tests

Maximum water penetration depth (mm)			
Mix	Delay time		
	0 min	15 min	60 min
SCRC0	17	16	17
SCRC20	14	15	14
SCRC50	12	12	13
SCRC100	11	11	13
Variation of maximum water penetration depth			
Mix	Delay time		
	0 min	15 min	60 min
SCRC0	1.00	0.94	1.00
SCRC20	1.00	1.07	1.00
SCRC50	1.00	1.00	1.08
SCRC100	1.00	1.00	1.18

Water permeability increases with w/c ratio and with the percentage of recycled aggregate. However, some studies showed that when the w/c ratio is low (around 0.45), the water penetration depth of recycled and conventional concretes is similar [THOM13]. Moreover, properly designed and cast, SCC can lead to a more homogeneous microstructure and denser interfacial zone with coarse aggregate particles, leading to low water penetration depths. In this work, the water penetration depth of all concretes is very low (Figure VIII-23).

Also, the variation of water penetration depth (penetration at a delay time / penetration at zero delay time) is shown in Table VIII-5. This variation is an index of the concrete thixotropy. A high thixotropic concrete shows a greater variation than a lower one. In this work, due to the low values of water penetration depth, it is difficult to discuss the differences of behaviour with the delay time between layers and with the replacement percentage. Only when the delay time is 60 min, it can be noted that for the total replacement percentage the increase in the variation of water penetration depth is slightly more noticeable (Figure VIII-24), which can be attributed, again, to the slightly higher thixotropy of SCRC100.

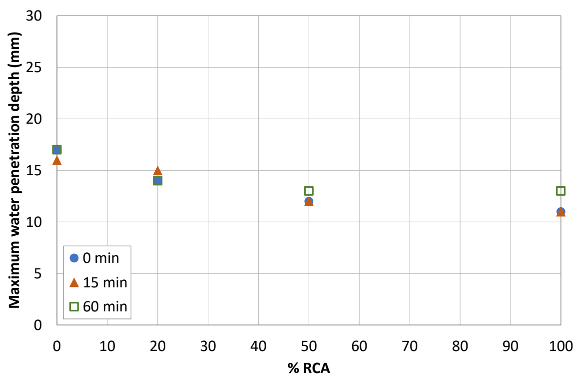


Figure VIII-23. Water penetration depth at each delay time vs. % RCA

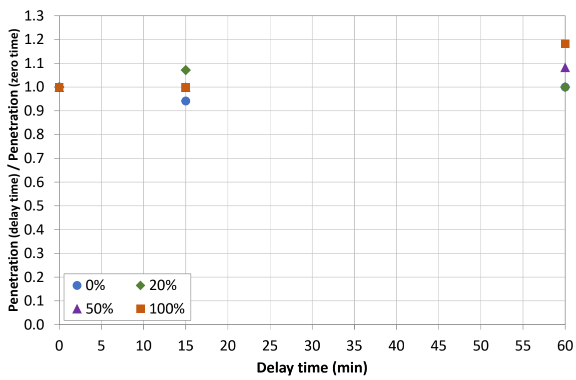


Figure VIII-24. Variation of water penetration depth for each % RCA vs. Delay time

4 CONCLUSIONS

The degree of thixotropy and the interlayer bond strength of self-compacting recycled concrete (SCRC) were evaluated using several testing methods and protocols. From the data presented in this chapter, the following conclusions can be made:

- Similar findings about the degree of thixotropy of each SCRC can be obtained with the three testing methods used, that is, they led to the same qualitative conclusions. It was also observed that the measurement of thixotropy throughout the structural breakdown curves and the yield stress at rest provide the most sensitive thixotropic indices.
- As thixotropy depends on the paste composition, and the paste composition of all concretes is similar, small differences in all SCRC mixes are found when analysing any of the thixotropic indices. Only a slight increase with the replacement percentage can be observed. This increase is due to the difference in the effective w/c ratio, result of the non–compensated water absorption, and to the higher amount of fines generated from the old mortar adhered to recycled coarse aggregate.
- Due to the effective w/c ratio designed in this phase (0.49), its changes over time are negligible. Thus, as the designed concretes are on the slight slope region of their "rheological variations – $(w/c)_{ef}$" curves, their evolution over time until the elapsed time of this working phase does not imply significant changes in the SCRC paste composition. Therefore, the thixotropic changing rate is similar in all studied mixes.
- Results obtained measuring the residual flexural strength and the variation in water penetration depth indicate that SCRCs hardly show differences in their interlayer bond strength when compared with the baseline SCC for the considered delay times. Only when the delay time is 60 min, it has been observed that for the total replacement percentage the decrease in the interlayer bond strength is slightly more noticeable. This is due to the fact that the thixotropy of the studied SCRCs is slightly higher when high replacement percentages are used.
- Lastly, when high percentages of recycled aggregate are used, when SCRC is designed with a low w/c ratio (on the high slope region of the "rheological variations – $(w/c)_{ef}$" curves) and/or when long term self-compacting behaviour is measured, the thixotropic changing rate and interlayer bond strength can be more affected in SCRC than in conventional SCC.

CHAPTER IX
Conclusions and future research

1 CONCLUSIONS

The experimental program carried out in order to develop this PhD dissertation has let the researchers obtain detailed conclusions, which were shown at the end of chapters IV to VIII. The most important of them can be summarised as follows.

1.1 Hardened-state behaviour of recycled concrete and self-compacting recycled concrete using database analysis

This work has focused on the prediction of some of the most important properties of structural vibrated recycled concrete (compressive strength, modulus of elasticity and splitting tensile strength) taking into account, not only the recycled percentage and the quality of the recycled aggregates used, but also the production method. With the results obtained, the following main conclusions can be drawn:

- In general, compressive strength, modulus of elasticity and splitting tensile strength of recycled concretes decrease as the recycled concrete coarse aggregate percentage increases. Taking into account the production methods (to pre-soak the recycled aggregates (*pre-soaked-PS*), to work with air-dry aggregates increasing the amount of water (*air-dry with extra-water-ADwEW*), or to work with air-dry aggregates without any extra water (*air-dry without extra-water-AD*)), it has been concluded that *ADwEW* during mixing shows the best results. With this method the reductions in compressive strength, splitting tensile strength and modulus of elasticity are lower (especially when compared with the PS method) and, moreover, there is no need to increase the dosage of superplasticiser.
- Regarding the modulus of elasticity, it has been seen that its prediction code expression (according to Eurocode) has to be corrected to get the same approximation degree in recycled concretes as in conventional ones. In this regard, using multivariable regression, a correction coefficient has been adjusted providing good statistical indexes. This correction coefficient takes into account the recycled concrete compressive strength, production procedure, replacement

ratio and recycled concrete coarse aggregate quality (considering it based on its water absorption). Different coefficients have been adjusted for each of the different mixing procedures.

- Regarding splitting tensile strength, it has been seen that its prediction code expression (according to Eurocode) does not need to be corrected to get the same approximation degree in recycled concretes as in conventional ones. The use of the compressive strength is enough to take into account the use of recycled aggregates.
- Lastly, specific expressions to predict the modulus of elasticity and the splitting tensile strength have been adjusted. For said purpose, the Eurocode expressions have been taken as a basis, modifying them to introduce the replacement ratio and the recycled concrete coarse aggregate quality (considering it, again, based on its water absorption). Also in this case, different expressions have been adjusted for each of the different mixing procedures considered, and the techniques used have been multivariable regression and genetic programming. In all cases, the expressions adjusted by means of genetic programming provide the best statistical indexes compared with the literature's proposals. Also, regarding the modulus of elasticity, the multivariable regression expressions improve the predictions proposed in the literature.

The prediction proposals obtained with vibrated recycled concrete have been used to study the behaviour of self-compacting recycled concrete, and their accuracy was analysed during the use of this concrete. Regarding these results, the main conclusions are as follows:

- As in vibrated recycled concrete, SCRC compressive strength, modulus of elasticity and splitting tensile strength decrease when the content of recycled coarse aggregate increases. It has been confirmed that, regarding these properties, the incorporation of recycled concrete coarse aggregate affects SCC to a similar extent as vibrated concrete.
- It has been stated that code expression does not provide the same approximation degree in SCRC as in SCC when calculating modulus of elasticity. Consequently, it has been corroborated that it is necessary to modify this expression by introducing a correction coefficient. Therefore, the suitability of the correction coefficient, adjusted to maintain the same approximation degree in both conventional and recycled vibrated concrete modulus prediction, was analysed. The results aim to conclude that it can be used with the same accuracy in vibrated recycled concrete as in SCRC.
- Regarding splitting tensile strength, it has been stated that code expression provides the same approximation degree in SCRC as in SCC. Consequently, it has been corroborated that, as in vibrated recycled concrete, it is not necessary to modify this expression by introducing a correction coefficient.
- Finally, accepting that code expressions (used in vibrated concrete) are suitable for the prediction of SCC modulus and splitting tensile strength, specific expressions adjusted in this work with vibrated recycled concrete can also be accepted for predicting SCRC modulus and splitting tensile strength. In this case, it has to be expected that, as occurs in conventional SCC, modulus prediction is going to overestimate SCRC modulus and splitting tensile prediction is going to underestimate SCRC splitting tensile strength.

1.2 Workability and rheology of self-compacting recycled concrete

It can be stated that the same relationships between empirical parameters and between empirical parameters and rheological properties can be used for conventional and recycled self-compacting concretes. The same tendency was observed in SCC as well as in SCRC regarding all relationships. All the limits established to the empirical parameters in SCC are suitable for SCRC. Only the PJ parameter seems to be too strict to analyse the blocking behaviour in SCRC. In this work, a PJ maximum value of 25 mm was determined. Moreover, according to all the obtained results and in agreement with other authors, none of the empirical tests was found to adequately cover all key characteristics of SCRC as a single test, and there is no combination of tests that has achieved universal approval.

The analysis of rheological behaviour showed that the specificity of SCRC lies in the quantity of extra water necessary to compensate for the recycled aggregate absorption during the mixing protocol, which affects the effective water to cement ratio, and in the intrinsic characteristics of recycled coarse aggregate (shape, texture and fines content). In this work, mainly the rough texture (since both natural and recycled coarse aggregates are crushed-shaped) and the fines content in the recycled aggregate and generated during mixing by the wear of old adhered mortar change the baseline mortar. All these singularities lead to different "rheological variations – $(w/c)_{ef}$" and "rheological property – $\emptyset/\emptyset_{max}$" curves in a SCRC compared to a SCC.

Finally, the differences obtained between SCC and SCRC behaviour over time depend on the quantity of water compensated in the mixing protocol that determines the region of the "rheological variations – $(w/c)_{ef}$" curves where the concrete has been designed (near or far from the high slope region). It is clear that the effective w/c ratio of SCRC evolves over time according to the evolution of the RCA water absorption. Then, it is more probable that the high slope region of the mentioned curves will be reached when high percentages of recycled aggregate are used, when SCRC is designed with a lower w/c ratio and/or when long term self-compacting behaviour is measured. In these cases, a different time-dependent rheological behaviour is expected from a SCRC than from a SCC, otherwise, the rheological behaviour over time of a SCRC will be similar to that of a SCC.

1.3 Robustness of self-compacting recycled concrete

The conclusion obtained with the sensitivity parameters and with the statistical approach leads to state that water is the key factor that affects SCRC robustness. Moreover, the statistical approach based on Kendall's coefficient of concordance and Spearman's rank correlation was successfully used to identify key properties of SCRC that can be measured to evaluate robustness: τ_0 (15 min), μ_{pl} (15 min), t500 (15 min), SF (15 min), SFJ (15 min) and SR.

SCRC is less robust than SCC. This is due to the fact that SCRC presents the "rheological parameter – $(w/c)_{ef}$" and "rheological parameter – $\emptyset/\emptyset_{max}$" curves with higher slope than the ones of conventional SCC. Then, when high percentages of recycled coarse aggregate are used, there is a greater possibility to reach the high slope region of high slope curves causing high yield stress changes (and similarly high plastic viscosity changes and high empirical parameters changes). Additionally, the use of aggregates with a moisture content makes it more difficult to design robust SCRCs, as it occurs with SCCs.

Hence, lastly, SCRC robustness will depend on the quantity of water compensated in the mixing protocol and on the region of the curve, "rheological parameter - $(w/c)_{ef}$", where the concrete has been designed (near or far from the high slope).

1.4 Thixotropy of self-compacting recycled concrete

Similar findings about the degree of thixotropy of each SCRC can be obtained with the three testing methods used, that is, they led to the same qualitative conclusions. It was also observed that the measurement of thixotropy throughout the structural breakdown curves and the yield stress at rest provide the most sensitive thixotropic indices.

As thixotropy depends on the paste composition, and the paste composition of all concretes is similar, small differences in all SCRC mixes are found when analysing any of the thixotropic indices. Only a slight increase with the replacement percentage can be observed. This increase is due to the difference in the effective w/c ratio, result of the non–compensated water absorption, and to the higher amount of fines generated from the old mortar adhered to recycled coarse aggregate.

Due to the effective w/c ratio designed in this phase (0.49), its changes over time are negligible. Thus, as the designed concretes are on the slight slope region of their “rheological variations – $(w/c)_{ef}$” curves, their evolution over time until the elapsed time of this working phase does not imply significant changes in the SCRC paste composition. Therefore, the thixotropic changing rate is similar in all studied mixes.

Results obtained measuring the residual flexural strength and the variation in water penetration depth indicate that SCRCs hardly show differences in their interlayer bond strength when compared with the baseline SCC for the considered delay times. Only when the delay time is 60 min, it has been observed that for the total replacement percentage the decrease in the interlayer bond strength is slightly more noticeable. This is due to the fact that the thixotropy of the studied SCRCs is slightly higher when high replacement percentages are used.

Lastly, when high percentages of recycled aggregate are used, when SCRC is designed with a low w/c ratio (on the high slope region of the “rheological variations – $(w/c)_{ef}$” curves) and/or when long term self-compacting behaviour is measured, the thixotropic changing rate and interlayer bond strength can be more affected in SCRC than in conventional SCC.

2 FUTURE RESEARCH

The following areas are recommended for future work:

- The study of a wide range of mix proportions to create workability boxes for multiple SCRC applications.
- The analysis of mortar rheology taking into account different percentages of fines from recycled coarse aggregate in its mix proportions (according to the different replacement percentages used in recycled concrete). These fines come from the loss of old adhered mortar and have an irregular shape and a rough texture, which affect the self-compacting behaviour. The key idea would be to define the “rheological variations – w/c” and “rheological variations – $\emptyset/\emptyset_{max}$” curves of each mortar and determine how they affect self-compacting recycled concrete.
- The study of the influence of recycled coarse aggregate on formwork pressures generated by SCRC.
- Finally, to continue with the idea of “green concrete”, the step forward would be to combine the use of recycled aggregate with the use of cements with reduced clinker content, using alternative raw materials. The idea behind “green concrete” is to describe and use concrete formulations which are optimized for the lowest possible environmental impact in all phases of the concrete structure's life cycle. Thus, while cement production in its beginnings only focused on ordinary Portland cement, later cements with several main constituents were produced by replacing parts of the clinker content by supplementary cementitious materials. As such, fly ash from coal power plants, granulated slag from iron production as well as natural pozzolans are used in increasing amounts. Also limestone can substitute some clinker in cement. Therefore, the substitution of clinker in cement is the most effective way to reduce the specific CO_2 emission per ton of cement. This joined to the substitution of natural aggregate with recycled one contributes to progress in the sustainable construction future.

CHAPTER X
References

REFERENCES CITED IN THE TEXT OF ALL CHAPTERS

[ACHE06] Alaejos, P., Sánchez, M., Vázquez, E., et al. (2006). Use of Recycled Aggregate in the Production of Structural Concrete (in Spanish). Commission 2, Working Group 2/5 Recycled concrete, Monograph M-11 ACHE, Madrid.

[AGRE11] Agrela, F., Sánchez de Juan, M., Ayuso, J., Geraldes, V. L., & Jiménez, J. R. (2011). Limiting properties in the characterisation of mixed recycled aggregates for use in the manufacture of concrete. *Construction and Building Materials*, 25(10), 3950-3955.

[AISS16] Aïssoun, B. M., Hwang, S-D., & Khayat, K. H. (2016). Influence of aggregate characteristics on workability of superworkable concrete. *Materials and Structures*, 49, 597-609.

[AJDU02] Ajdukiewicz, A., & Kliszczewicz, A. (2002). Influence of recycled aggregates on mechanical properties of HS/HPC. *Cement and Concrete Composites*, 24(2), 269–279.

[AKBA11] Akbarnezhad, A., Ong, K. C. G., Zhang, M. H., Tam, C. T., & Foo, T. W. J. (2011). Microwave-assisted beneficiation of recycled concrete aggregates. *Construction and Building Materials*, 25(8), 3469-3479.

[AKBA13] Akbarnezhad, A., Ong, K. C. G., Tam, C. T., & Zhang, M. H. (2013). Effects of the parent concrete properties and crushing procedure on the properties of coarse recycled concrete aggregates. *Journal of Materials in Civil Engineering,* 25(12), 1795-1802.

[ALON07] Alonso, M. M., Palacios, M., Puertas, F., de la Torre, A. G., & Aranda, M. A. G. (2007). Effect of polycarboxylate admixture structure on cement paste rheology. *Materiales de Construcción*, 57(286), 65-81.

[ANGU10] Angulo, S. C., Carrijo, P. M., Figueiredo, A. D., Chaves, A. P., & John, V. M. (2010). On the classification of mixed construction and demolition waste aggregate by porosity and its impact on the mechanical performance of concrete. *Materials and Structures*, 43(4), 519-528.

[ASGH16] Asghari, A. A., Hernández, A. M. L., Feys, D., & De Schutter, G. (2016). Which parameters, other than the water content, influence the robustness of cement paste with SCC consistency? *Construction and Building Materials*, 124, 95-103.

[ASSA04] Assaad, J. (2004). Formwork Pressure of Self-Consolidating Concrete - Influence of Thixotropy. PhD Dissertation, University of Sherbrooke, Canada.

[ASSA09] Assaad, J., Harb, J., & Chakar, E. (2009). Relationships between key ASTM test methods determined on concrete and concrete-equivalent mortar mixtures. *Journal of ASTM International*, 6(3), 1–13.

[BAIR93] Bairagi, N. K., Ravande, K., & Pareek, V. K. (1993). Behaviour of concrete with different proportions of natural and recycled aggregates. *Resources, Conservation and Recycling*, 9(1-2), 109-126.

[BANF03] Banfill, P.F.G. (2003). The rheology of fresh cement and concrete — a review. Proceedings, 11th International Congress on the Chemistry of Cement, Durban, South Africa, 1, 50–62.

[BANF06] Banfill, P. F. G. (2006). Rheology of fresh cement and concrete. The British Society of Rheology, School of the Built Environment, Heriot-Watt University, Edinburgh, UK, pp. 61-130.

[BANF11] Banfill, P. F. G. (2011). Additivity effects in the rheology of fresh concrete containing water-reducing admixtures. *Construction and Building Materials*, 25, 2955-2960.

[BARB13] Barbudo, A., De Brito, J., Evangelista, L., Bravo, M., & Agrela, F. (2013). Influence of water-reducing admixtures on the mechanical performance of recycled concrete. *Journal of Cleaner Production*, 59, 93-98.

[BARN00] Barnes, H. A. (2000). A handbook of elementary rheology. Institute of Non-Newtonian Fluid Mechanics, University of Wales. ISBN: 0-9538032-0-1.

[BARN97] Barnes, H. A. (1997). Thixotropy – A review. *Journal of Non-Newtonian Fluid Mechanics*, 70, 1-33.

[BARR97] Barra, M., & Vázquez, E. (1997). Particularidades do proceso de carbonatação em concretos de agregado reciclado. IV Congreso Iberoamericano de Patología de las Construcciones, VI Congreso de Control y Calidad, Octubre 1997, Brasil.

[BEAU94] Beaupré, D. (1994). Rheology of high performance shotcrete. PhD Dissertation, University of British Columbia, Canada.

[BEHE14] Behera, M., Bhattacharyya, S. K., Minocha, A. K., Deoliya, R., & Maiti, S. (2014). Recycled aggregate from C&D waste & its use in concrete – A breakthrough towards sustainability in construction sector: A review. *Construction and Building Materials*, 68, 501-516.

[BEHN15] Behnood, A., Olek, J., & Glinicki, M. A. (2015). Predicting modulus elasticity of recycled aggregate concrete using M5' model tree algorithm. *Construction and Building Materials*, 94, 137-147.

[BELI14] Belin, P., Habert, G., Thiery, M., & Roussel, N. (2014). Cement paste content and water absorption of recycled concrete coarse aggregates. *Materials and Structures*, 47(9), 1451-1465.

[BERN09] Berndt, M. L. (2009). Properties of sustainable concrete containing fly ash, slag and recycled concrete aggregate. *Construction and Building Materials*, 23(7), 2606-2613.

[BHIK10] Bhikshma, V., & Kishore, R. (2010). Development of stress - strain curves for recycled aggregate concrete. *Asian Journal of Civil Engineering*, 11(2), 253-261.

[BILL06] Billberg, P. (2006). Form Pressure Generated by Self-Compacting Concrete — Influence of Thixotropy and Structural Behaviour at Rest. PhD Dissertation. School of Architecture and the Built

Environment, Division of Concrete Structures Royal Institute of Technology SE-100 44 Stockholm, Sweden.

[BILL11] Billberg, P. (2011). The structural behaviour of SCC at rest. 36th Conference on *Our World in Concrete & Structures*, 14 - 16 August 2011, Singapore.

[BILL12] Billberg, P. (2012). SCC Mixture Design and its Influence on Rheology. Factors affecting the rheology of SCC and how to control it. International Workshop on Self-Compacting Concrete, June 1st 2012, Stockholm, Sweden.

[BOGA15] Bogas, J. A., De Brito, J., & Figueiredo, J. M. (2015). Mechanical characterization of concrete produced with recycled lightweight expanded clay aggregate concrete. *Journal of Cleaner Production*, 89, 187–195.

[BONE07] Bonen, D. (2007). Chapter 1. Robustness of SCC. In *Self-Consolidating Concrete* (pp. 4-22). A White Paper by Researchers at The Center of Advanced Cement Based Materials (ACBM).

[BOUD16] Boudali, S., Kerdal, D. E., Ayed, K., Abdulsalam, B., & Soliman, A. M. (2016). Performance of self-compacting concrete incorporating recycled concrete fines and aggregate exposed to sulphate attack. *Construction and Building Materials*, 124, 705-713.

[BRAN15] Brand, A. S., Roesler, J. R., & Salas, A. (2015). Initial moisture and mixing effects on higher quality recycled coarse aggregate concrete. *Construction and Building Materials*, 79, 83-89.

[BRIT10] De Brito, J., & Robles, R. (2010). Recycled aggregate concrete (RAC) methodology for estimating its long-term properties. *Indian Journal of Engineering & Materials Sciences*, 17, 449-462.

[BRIT16] De Brito, J., Ferreira, J., Pacheco, J., Soares, D., & Guerreiro, M. (2016). Structural, material, mechanical and durability properties and behaviour of recycled aggregates concrete. *Journal of Building Engineering*, 6, 1-16.

[BS8500:02] BS 8500-2:2002. Concrete-Complementary British Standard to BS EN 206-1. Part 2: Specification for Constituent Materials and Concrete.

[BSI02] BSI (British Standards Institution) (2002). BS 8500-2: Concrete – complementary British standard to BS EN 206-1. Part 2: Specification for constituent materials and concrete. BSI, London.

[BUTL13] Butler, L., West, J. S., & Tighe, S. L. (2013). Effect of recycled concrete coarse aggregate from multiple sources on the hardened properties of concrete with equivalent compressive strength. *Construction and Building Materials*, 47, 1292–1301.

[CABR11] Cabrera, O. A., Traversa, L. P., & Ortega, N. F. (2011). Effect of crushed sand on mortar and concrete rheology. *Materiales de Construcción*, 61(303), 401-416.

[CARR05] Carrijo, P. (2005). Analysis of the influence of the density of coarse aggregates from construction and demolition waste on the mechanical performance of concrete. Master Dissertation, University of São Paulo, Brazil.

[CARR15] Carro-López, D., González-Fonteboa, B., de Brito, J., Martínez-Abella, F., González-Taboada, I., & Silva, P. (2015). Study of the rheology of self-compacting concrete with fine recycled concrete aggregates. *Construction and Building Materials*, 96, 491–501.

[CASU08] Casuccio, M., Torrijos, M. C., Giaccio, G., & Zerbino, R. (2008). Failure mechanism of recycled aggregate concrete. *Construction and Building Materials*, 22(7), 1500-1506.

[CHAI97] Chai, H-W. Design and testing of self-compacting concrete. PhD Dissertation, University of London, 1997.

[CHAK11] Chakradhara Rao, M., Bhattacharyya, S. K., & Barai, S. V. (2011). Influence of field recycled coarse aggregate on properties of concrete. *Materials and Structures*, 44(1), 205-220.

[CHAN10] Chan, K. D., Ong, K. C. G., & Tam, C. T. (2010). Passing ability of SCC – Improved method based on the P-Ring. 35th Conference on *Our World in Concrete & Structures*, 25 - 27 August 2010, Singapore.

[CHOP04] Chopin, D., De Larrard, L., & Cazacliu, B. (2004). Why do HPC and SCC require a longer mixing time? *Cement and Concrete Research*, 34(12), 2237-2243.

[CLAD14] Cladera, A., Pérez-Ordóñez, J. L., & Martínez-Abella, F. (2014). Shear strength of RC beams. Precision, accuracy, safety and simplicity using genetic programming. *Computers and Concrete*, 14(4), 479-501.

[COLL15] Collery, D. J., Paine, K. A., & Dhir, R. K. (2015). Establishing rational use of recycled aggregates in concrete: a performance-related approach. *Magazine of Concrete Research*, 67 (11), 559-574.

[CORI09] Corinaldesi, V., & Moriconi, G. (2009). Influence of mineral additions on the performance of 100% recycled aggregate concrete. *Construction and Building Materials*, 23(8), 2869–2876.

[CORI10a] Corinaldesi, V. (2010). Mechanical and elastic behaviour of concretes made of recycled-concrete coarse aggregates. *Construction and Building Materials*, 24(9), 1616-1620.

[CORI10b] Corinaldesi, V., & Moriconi, G. (2010). Recycling of rubble from building demolition for low-shrinkage concretes. *Waste Management*, 30(4), 655-659.

[CORI11a] Corinaldesi, V. (2011). Structural concrete prepared with coarse recycled concrete aggregate: From investigation to design. *Advances in Civil Engineering*, 2011.

[CORI11b] Corinaldesi, V., Letelier, V., & Moriconi, G. (2011). Behaviour of beam-column joints made of recycled-aggregate concrete under cyclic loading. *Construction and Building Materials*, 25(4), 1877-1882.

[CORI11c] Corinaldesi, V., & Moriconi, G. (2011). The role of industrial by-products in self compacting concrete. *Construction and Building Materials*, 25, 3181-3186.

[DAPE11] Dapena, E., Alaejos, P., Lobet, A., & Pérez, D. (2011). Effect of Recycled Sand Content on Characteristics of Mortars and Concretes. *Journal of Materials in Civil Engineering*, 23(4), 414–422.

[DEBI10] Debieb, F., Courard, L., Kenai, S., & Degeimbre, R. (2010). Mechanical and durability properties of concrete using contaminated recycled aggregates. *Cement and Concrete Composites*, 32(6), 421-426.

[DEEB13] Deeb, R. (2013). Flow of self-compacting concrete. PhD Dissertation. School of Engineering, Cardiff University, UK.

[DHIR99] Dhir, R. K., Limbachiya, M. C., & Leelawat, T. (1999). Suitability of recycled aggregate for use in BS 5328 designated mixes. Proceedings of the Institution of Civil Engineers, 134, 257-274.

[DILL98] Dillmann, R. (1998). Concrete with recycled concrete aggregate. In: Proceedings of International Symposium on Sustainable Construction: Use of Recycled Concrete Aggregate, Dundee, Scotland, 1998, 239–253.

[DIN02] DIN (Deutsches Institut für Normung) (2002). DIN 4226-100: 2002-2: Aggregates for mortar and concrete. Part 100: recycled aggregates. DIN, Berlin.

[DJER12] Djerbi Tegguer, A. (2012). Determining the water absorption of recycled aggregates utilizing hydrostatic weighing approach. *Construction and Building* Materials, 27(1), 112-116.

[DOMI09] Domingo-Cabo, A., Lázaro, C., López-Gayarre, F., Serrano-López, M. A., Serna, P., & Castaño-Tabares, J. O. (2009). Creep and shrinkage of recycled aggregate concrete. *Construction and Building Materials*, 23(7), 2545-2553.

[DOMI10] Domingo, A., Lázaro, C., Gayarre, F. L., Serrano, M. A., & López-Colina, C. (2010). Long term deformations by creep and shrinkage in recycled aggregate concrete. *Materials and Structures*, 43(8), 1147–1160.

[DOMO06] Domone, P. L. (2006). Self-compacting concrete: An analysis of 11 years of case studies. *Cement and Concrete Composites*, 28, 197–208.

[DOMO07] Domone, P. L. (2007). A review of the hardened mechanical properties of self-compacting concrete. *Cement and Concrete Composites*, 29, 1–12.

[DOMO88] Domone, P. L., & Thurairatnam, H. (1988). The effect of water/cement ratio, plasticizers and temperature on the rheology of cement grouts. *Advances in Cement Research*, 1(4), 203–214.

[DONG12] Dong-Woo, K., & Hee-Bok, C. (2012). Hydration Analysis of Fine Particle and Old Mortar Attached on the Surface of Recycled Aggregate. *Journal of the Korea Institute of Building Construction*, 12(5), 460-467.

[DUAN13a] Duan, Z. H., Kou, S. C., & Poon, C. S. (2013). Prediction of compressive strength of recycled aggregate concrete using artificial neural networks. *Construction and Building Materials,* 40, 1200-1206.

[DUAN13b] Duan, Z. H., Kou, S. C., & Poon, C. S. (2013). Using artificial neural networks for predicting the elastic modulus of recycled aggregate concrete. *Construction and Building Materials,* 44, 524-532.

[EFNARC02] EFNARC (2002). Specification and Guidelines for Self-Compacting Concrete. Farnham, UK: European Federation of Producers and Contractors of Specialist Products for Structures.

[EFNARC05] EFNARC, BIBM, ERMCO, CEMBUREAU, EFCA (2005). The European guidelines for self-compacting concrete. Specification, production and use.

[EHE08] EHE-08 - Spanish Instruction for Structural Concrete (2008). Ministry of Public Works, August-08 (in Spanish).

[EN1097-6] EN 1097-6. Tests for mechanical and physical properties of aggregates. Part 6: Determination of particle density and water absorption.

[EN12350-10] EN 12350-10: Testing fresh concrete. Part 10: Self-compacting concrete. L-box test.

[EN12350-11] EN 12350-11: Testing fresh concrete. Part 11: Self-compacting concrete. Sieve segregation test.

[EN12350-12] EN 12350-12: Testing fresh concrete. Part 10: Self-compacting concrete. J-Ring test.

[EN12350-2] EN 12350-2: Testing fresh concrete. Part 2: Slump-test.

[EN12350-6] EN 12350-6. Testing fresh concrete. Part 6: Density.

[EN12350-8] EN 12350-8: Testing fresh concrete. Part 8: Self-compacting concrete. Slump-flow test.

[EN12350-9] EN 12350-9: Testing fresh concrete. Part 9: Self-compacting concrete. V-funnel test.

[EN12390-13] EN 12390-13. Testing hardened concrete. Part 13: Determination of secant modulus of elasticity in compression.

[EN12390-3] EN 12390-3. Testing hardened concrete. Part 3: Compressive strength of test specimens.

[EN12390-6] EN 12390-6. Testing hardened concrete. Part 6: Tensile splitting strength of test specimens.

[EN12390-7] EN 12390-7. Testing hardened concrete. Part 7: Density of hardened concrete.

[EN12390-8] EN 12390-8: Testing hardened concrete. Part 8: Depth of penetration of water under pressure.

[EN196-1] EN 196-1. Methods of testing cement. Part 1: Determination of strength.

[EN196-3] EN 196-3. Methods of testing cement. Part 3: Determination of setting times and soundness.

[EN197-1] EN 197-1. Cement. Part 1: Composition, specifications and conformity criteria for common cements.

[EN206-9] EN 206-9: Concrete. Part 9: Additional rules for self-compacting concrete (SCC).

[EN933-1] EN 933-1. Tests for geometrical properties of aggregates. Part 1: Determination of particle size distribution. Sieving method.

[EN933-11] EN 933-11. Tests for geometrical properties of aggregates. Part 11: Classification test for the constituents of coarse recycled aggregate.

[EN933-3] EN 933-3. Tests for geometrical properties of aggregates. Part 3: Determination of particle shape. Flakiness index.

[ERDO05] Erdogăn, S. T. (2005). Determination of aggregate shape properties using X-ray tomographic methods and the effect of shape on concrete rheology. PhD Dissertation. University of Texas at Austin.

[ERDO08] Erdogăn, S. T., Martys, N. S., Ferraris, C. F., & Fowler, D. W. (2008). Influence of the shape and roughness of inclusions on the rheological properties of a cementitious suspension. *Cement and Concrete Composites*, 30, 393-402.

[ETXE06] Etxeberria, M., Vázquez, E., & Marí, A. (2006). Microstructure analysis of hardened recycled aggregate concrete. *Magazine of Concrete Research*, 58(10), 683-690.

[ETXE07a] Etxeberria, M., Marí, A. R., & Vázquez, E. (2007). Recycled aggregate concrete as structural material. *Materials and Structures*, 40(5), 529-541.

[ETXE07b] Etxeberria, M., Vázquez, E., Marí, A., & Barra, M. (2007). Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete. *Cement and Concrete Research*, 37(5), 735-742.

[EURO04] European Committee for Standardization, "Eurocode 2: Design of concrete structures", Brussels, 2004.

[EVAN07] Evangelista, L., & de Brito, J. (2007). Mechanical behaviour of concrete made with fine recycled concrete aggregates. *Cement and Concrete Composites*, 29(5), 397-401.

[EVAN10] Evangelista, L., & de Brito, J. (2010). Durability performance of concrete made with fine recycled concrete aggregates. *Cement and Concrete Composites*, 32(1), 9-14.

[FAKI12] Fakitsas, C., Papakonstantinou, P., Kiousis, P., & Savva, A. (2012). Effects of Recycled Concrete Aggregates on the Compressive and Shear Strength of High-Strength Self-Consolidating Concrete. *Journal of Materials in Civil Engineering*, 24(4), 356-361.

[FALE14] Faleschini, F., Jiménez, C., Barra, M., Aponte, D., Vázquez, E., & Pellegrino, C. (2014). Rheology of fresh concretes with recycled aggregates. *Construction and Building Materials*, 73, 407-416.

[FATH10] Fathifazl, G., Abbas, A., Razaqpur, A. G., Isgor, O. B., Fournier, B., & Foo, S. (2010). New Mixture Proportioning Method for Concrete Made with Coarse Recycled Concrete Aggregate. *Journal of Materials in Civil Engineering*, 21(10), 601-611.

[FATH11] Fathifazl, G., Ghani Razaqpur, A., Burkan Isgor, O., Abbas, A., Fournier, B., & Foo, S. (2011). Creep and drying shrinkage characteristics of concrete produced with coarse recycled concrete aggregate. *Cement and Concrete Composites*, 33(10), 1026–1037.

[FERR00] Ferraris, C. F., Brower, L., Ozyildirim, C., & Daczko, J. (2000). Workability of Self-Compacting Concrete. National Institute of Standards and Technology, reprinted from The Economical Solution for Durable Bridges and Transportation Structures, International Symposium on High Performance Concrete. Proceedings. PCI/FHWA/FIB. 25-27 September 2000, Orlando, Florida, 398-407.

[FERR01] Fresh Concrete Rheology: Recent Developments. National Institute of Standards and Technology, reprinted from Materials Science of Concrete VI, Sidney Mindess and Jan Skalny, eds., The American Ceramic Society, 735 Ceramic Place, Westerville, OH 43081, 215-241.

[FERR03] Ferraris, C. F., & Brower, L. E. (2003). Comparison of Concrete Rheometers. *Concrete International*, 25 (8), 41-47.

[FERR07] Ferron, R. P., Gregori, A., Sun, Z., & Shah, S. P. (2007). Rheological Method to Evaluate Structural Buildup in Self-Consolidating Concrete Cement Pastes. *ACI Materials Journal*, 104(3), 242-250.

[FERR11] Ferreira, L., De Brito, J., & Barra, M. (2011). Influence of the pre-saturation of recycled coarse concrete aggregates on concrete properties. *Magazine of Concrete Research*, 63(8), 617-627.

[FERR98] Ferraris, C. F., & de Larrard, F. (1998). Modified Slump Test to Measure Rheological Parameters of Fresh Concrete. *Cement, Concrete and Aggregates*, 20(2), 241-247.

[FEYS07] Feys, D., Verhoeven, R., & De Schutter, G. (2007). Evaluation of Time Independent Rheological Models Applicable to Fresh Self-Compacting Concrete. *Applied Rheology*, 17(5), 56244-1 – 56244-10.

[FEYS13] Feys, D., Wallevik, J. E., Yahia, A., Khayat, K. H., & Wallevik, O. H. (2013). Extension of the Reiner–Riwlin equation to determine modified Bingham parameters measured in coaxial cylinders rheometers. *Materials and Structures*, 46, 289-311.

[FLAT04] Flatt, R. J. (2004). Dispersion forces in cement suspensions. *Cement and Concrete Research*, 34 (3), 399–408.

[FONS11] Fonseca, N., de Brito, J., & Evangelista, L. (2011). The influence of curing conditions on the mechanical performance of concrete made with recycled concrete waste. *Cement and Concrete Composites*, 33(6), 637-643.

[GEIK02] Geiker, M. R., Brandl, M., Thrane, L., & Nielsen, L. F. (2002). On the effect of coarse aggregate fraction and shape on the rheological properties of self-compacting concrete. *Cement, Concrete and Aggregates*, 24(1), 3–6.

[GESO15a] Gesŏglu, M., Güneyisi, E., Öz, H. Ö., Taha, I., & Yasemin, M. T. (2015). Failure characteristics of self-compacting concretes made with recycled aggregates. *Construction and Building Materials*, 98, 334-344.

[GESO15b] Gesŏglu, M., Güneyisi, E., Öz, H. Ö., Yasemin, M. T., & Taha, I. (2015). Durability and Shrinkage Characteristics of Self-Compacting Concretes Containing Recycled Coarse and/or Fine Aggregates. *Advances in Materials Science and Engineering*, 2015, article ID 278296, 18 pp.

[GETT09] Gettu, R., Shareef, S. N., & Ernest, K. J. D. (2009). Evaluation of the robustness of SCC. *The Indian Concrete Journal*, 83(6), 13-19.

[GOME02] Gómez-Soberón, J. M. V. (2002). Porosity of recycled concrete with substitution of recycled concrete aggregate: An experimental study. *Cement and Concrete Research*, 32(8), 1301-1311.

[GONÇ10] Gonçalves, P., & De Brito, J. (2010). Recycled aggregate concrete (RAC) - comparative analysis of existing specifications. *Magazine of Concrete Research*, 62(5), 339-346.

[GONZ02] González-Fonteboa, B. (2002). Hormigones con áridos reciclados procedentes de demoliciones: dosificación, propiedades mecánicas y comportamiento estructural a cortante. PhD Dissertation, University of A Coruña, Spain.

[GONZ05] González-Fonteboa, B., & Martínez -Abella, F. (2005). Recycled aggregates concrete: Aggregate and mix properties [Hormigones con áridos reciclados: Estudio de propiedades de los áridos y de las mezclas]. *Materiales De Construcción*, 55(279), 53-66.

[GONZ08] González-Fonteboa, B., & Martínez-Abella, F. (2008). Concretes with aggregates from demolition waste and silica fume: materials and mechanical properties. *Building and Environment*, 43(4), 429-437.

[GONZ11a] González-Fonteboa, B., Martínez-Abella, F., Eiras-López, J., & Seara-Paz, S. (2011). Effect of recycled coarse aggregate on damage of recycled concrete. *Materials and Structures*, 44, 1759-1771.

[GONZ11b] González, B., Martínez, F., Carro, D., & Seara, S. (2011). Stress-strain relationship in axial compression for concrete using recycled saturated coarse aggregate. *Construction and Building Materials*, 25(5), 2335-2342.

[GONZ14] González-Corominas, A., & Etxeberria, M. (2014). Experimental analysis of properties of high performance recycled aggregate concrete. *Construction and Building Materials*, 52, 227–235.

[GONZ16] González-Corominas, A., & Etxeberria, M. (2016). Effects of using recycled concrete aggregates on the shrinkage of high performance concrete. *Construction and Building Materials*, 115, 32-41.

[GRDI10] Grdic, Z. J., Toplicic-Curcic, G. A., Despotovic, I. M., & Ristic, N. S. (2010). Properties of self-compacting concrete prepared with coarse recycled concrete aggregate. *Construction and Building Materials*, 24(7), 1129-1133.

[GRIS15] Grist, E., Paine, K., Heath, A., Norman, J., & Pinder, H. (2015). Structural and durability properties of hydraulic lime-pozzolan concretes. *Cement and Concrete Composites*, 62, 212-223.

[GUNE14] Güneyisi, E., Gesŏglu, M., Algin, Z., & Yazici, H. (2014). Effect of surface treatment methods on the properties of self-compacting concrete with recycled aggregates. *Construction and Building Materials*, 64, 172–183.

[GUNE16] Güneyisi, E., Gesŏglu, M., Algin, Z., & Yazici, H. (2016). Rheological and fresh properties of self-compacting concretes containing coarse and fine recycled concrete aggregates. *Construction and Building Materials*, 113, 622-630.

[HANS83] Hansen, T. C., & Narud, H. (1983). Strength of recycled concrete made from crushed concrete coarse aggregate. *Concrete International*, 5(1), 79-83.

[HU05] Hu, J. (2005).A study of effects of aggregate on concrete rheology. PhD Dissertation, Iowa State University, Ames, Iowa.

[HWAN06] Hwang, S-D., Khayat, K. H., & Bonneau, O. (2006). Performance-Based Specifications of Self-Consolidating Concrete Used in Structural Applications. *ACI Materials Journal*, 103(2), 121-129.

[ICAR07] ICAR (2007). ICAR Rheometer Users Manual.

[JIN02] Jin, J. (2002). Properties of mortar for self-compacting concrete. PhD Dissertation, University of London.

[JIS05] Japanese Standards Association (2005) (JIS A 5021). Recycled Aggregate for Concrete-class H. Japanese Standards Association, Tokyo.

[JIS06] Japanese Standards Association (2006) (JIS A 5022). Recycled Aggregate for Concrete-class M. Japanese Standards Association, Tokyo.

[JIS07] Japanese Standards Association (2007) (JIS A 5023). Recycled Aggregate for Concrete-class L. Japanese Standards Association, Tokyo.

[JUAN04] De Juan, M. S. (2004). Estudio sobre la utilización de árido reciclado para la fabricación de Hormigón Estructural. PhD Dissertation, Polytechnic University of Madrid, Spain.

[JUAN09] De Juan, M. S., & Gutiérrez, P. A. (2009). Study on the influence of attached mortar content on the properties of recycled concrete aggregate. *Construction and Building Materials*, 23(2), 872-877.

[KAKI88] Kakizaki, M., Harada, M., Soshiroda, T., Kubota, S., Ikeda, T., & Kasai, Y. (1988). Strength and elastic modulus of recycled aggregate concrete. Proceedings of the 2nd International RILEM Symposium on Demolition and Reuse of Concrete and Masonry, 7-11 November 1988, Tokyo, Japan, 726-735.

[KATZ03] Katz, A. (2003). Properties of concrete made with recycled aggregate from partially hydrated old concrete. *Cement and Concrete Research*, 33(5), 703-711.

[KEBA15] Kebaïli, O., Mouret, M., Arabi, N., & Cassagnabere, F. (2015). Adverse effect of the mass substitution of natural aggregates by air-dried recycled concrete aggregates on the self-compacting ability of concrete: evidence and analysis through an example. *Journal of Cleaner Production*, 87, 752-761.

[KEND39] Kendall, M. G., & Babington Smith, B. (1939). The Problem of m rankings. *The Annals of Mathematical Statistics*, 10(3), 275-287.

[KEND90] Kendall, M., & Gibbons, J. D. (1990). Rank correlation methods (fifth edition). USA, Oxford University Press. ISBN: 0-85264-305-5.

[KHAY02] Khayat, K., Saric-Coric, M., & Liotta, F. (2002). Influence of Thixotropy on Stability Characteristics of Cement Grout and Concrete. *ACI Materials Journal*, 99(3), 234-241.

[KHAY03] Khayat, K. H., & Assaad, J. (2003). Relationship between washout resistance and rheological properties of high-performance underwater concrete. *ACI Materials Journal*, 100(3), 185-193.

[KHAY07] Khayat, K. H., & Omran, A. (2007). SCC formwork pressure. Phase II - State-of-the-art. Review of formwork pressure exerted by self-consolidating concrete. Submitted to The National Ready-mix Concrete Research Foundation and The Strategic Development Council, American Concrete Institute. University of Sherbrooke, Canada.

[KHAY08] Khayat, K. H., & Mitchell, D. (2008). Research Description and Findings to Self-Consolidating Concrete for Precast, Prestressed Concrete Bridge Elements. Final Report for NCHRP Project 18-12.

[KHAY12a] Khayat, K. H., Omran, A., & Magdi, W. A. (2012). Evaluation of thixotropy of self-consolidating concrete and influence on concrete performance. I Simpósio latinoamericano sobre concreto autodensável, October 8-10, Maceió-Alagoas, Brazil.

[KHAY12b] Khayat, K. H., Hwang, S-D., & Naji, S. (2012). Evaluation of robustness of SCC to variations in sand humidity and superplasticizer dosage. ACI Spring 2012 Convention, March 18-21, Dallas, TX.

[KIM13] Kim, S., Choi, H., Shin, Y., Kim, G., & Seo, D. (2013). Optimizing the mixing proportion with neural networks based on genetic algorithms for recycled aggregate concrete. *Advances in Materials Science and Engineering,* 2013, article ID 527089, 10 pp.

[KOEH03] Koehler, E. P., & Fowler, D. W. (2003). Summary of Concrete Workability Test Methods. (Research Report ICAR 105-1). International Center for Aggregates Research, Austin, TX.

[KOEH04] Koehler, E. P., & Fowler, D. W. (2004). Development of a portable rheometer for fresh Portland cement concrete (Research Report ICAR 105-3F). International Center for Aggregates Research, Austin, TX.

[KOEH06] Koehler, E. P., & Fowler, D. W. (2006). Development and Use of a Portable Rheometer for Concrete. Supplementary Proceedings of the Eighth CANMET/ACI International Conference on Recent Advances in Concrete Technology, Montreal, Canada, May 31-June 3 2006, 53-72.

[KOEH07] Koehler, E. P., & Fowler, D. W. (2007). ICAR Mixture Proportioning Procedure for Self-Consolidating Concrete (Research Report ICAR 108-1). International Center for Aggregates Research, Austin, TX.

[KOEH08] Koehler, E. P., & Fowler, D. W. (2008). Static and dynamic yield stress measurements of SCC. SCC 2008 Conference Proceedings, November 10-12, Chicago, IL.

[KOEH09] Koehler, E. P. (2009). Use of Rheology to Specify, Design, and Manage Self-Consolidating Concrete. Proceedings of the Tenth ACI International Symposium on Recent Advances in Concrete Technology and Sustainability Issues, Sevilla, Spain.

[KONG10] Kong, D., Lei, T., Zheng, J., Ma, C., Jiang, J., & Jiang, J. (2010). Effect and mechanism of surface-coating pozzolanics materials around aggregate on properties and ITZ microstructure of recycled aggregate concrete. *Construction and Building Materials*, 24(5), 701-708.

[KOU04] Kou, S. C., Poon, C. S., & Chan, D. (2004). Properties of steam cured recycled aggregate fly ash concrete. International RILEM Conference on Use of Recycled Materials in Buildings and Structures, Barcelona, 590-599.

[KOU08] Kou, S. C., Poon, C. S., & Chan, D. (2008). Influence of fly ash as a cement addition on the hardened properties of recycled aggregate concrete. *Materials and Structures*, 41(7), 1191-1201.

[KOU09] Kou, S. C., & Poon, C. S. (2009). Properties of self-compacting concrete prepared with coarse and fine recycled concrete aggregates. *Cement and Concrete Composites*, 31(9), 622-627.

[KOVL11] Kovler, K., & Roussel, N. (2011). Properties of fresh and hardened concrete. *Cement and Concrete Research*, 41, 775-792.

[KWAN10] Kwan, A. K. H., & Ng, I. Y. T. (2010). Improving performance and robustness of SCC by adding supplementary cementitious materials. *Construction and Building Materials*, 24, 2260-2266.

[LARR95] De Larrad, F., Hu, C., Szitkar, J. C., Joly, M., Claux, F., & Sedran, T. (1995). A New Rheometer for Soft-to-Fluid Fresh Concrete. LCPC Internal Report.

[LARR98] De Larrard, F., Ferraris, C. F., & Sedran, T. (1998). Fresh concrete: A Herschel-Bulkley material. *Materials and Structures*, 31, 494-498.

[LASE16] Laserna, S., & Montero, J. (2016). Influence of natural aggregates typology on recycled concrete strength properties. *Construction and Building Materials*, 115, 78-86.

[LASK11] Laskar, A. I., & Bhattacharjee, R. (2011). Torque–speed relationship in a concrete rheometer with vane geometry. *Construction and Building Materials*, 25, 3443–3449.

[LEIT01] Leite, M. (2001). Evaluation of the mechanical properties of concrete made with recycled aggregates from construction and demolition waste. PhD Dissertation, Federal University of Rio Grande do Sul, Porto Alegre, Brazil.

[LI08] Li, Xuping (2008). Recycling and reuse of waste concrete in china: Part I. Material behaviour of recycled aggregate concrete. *Resources, Conservation and Recycling*, 53, 36-44.

[LI12] Li, W., Xiao, J., Sun, Z., Kawashima, S., & Shah, S. P. (2012). Interfacial transition zones in recycled aggregate concrete with different mixing approaches. *Construction and Building Materials*, 35, 1045-1055.

[LIMA14] Lima, P. R. L., Toledo-Filho, R. D., & Gomes, O. F. M. (2014). Influence of Recycled Aggregate on the Rheological Behavior of Cement Mortar. *Key Engineering Materials*, 600, 297-307.

[LNEC06] LNEC (National Laboratory of Civil Engineering) (2006). LNEC E 471. Guideline for the Use of Recycled Coarse Aggregates in Hydraulic Binders' Concrete. National Laboratory of Civil Engineering. Portugal (in Portuguese).

[LOPE08] López, F. (2008). Influencia de la variación de los parámetros de dosificación y fabricación de hormigón reciclado estructural sobre sus propiedades físicas y mecánicas. PhD Dissertation, University of Oviedo, Spain.

[LOPE14] López Gayarre, F., López-Colina Pérez, C., Serrano López, M. A., & Domingo Cabo, A. (2014). The effect of curing conditions on the compressive strength of recycled aggregate concrete. *Construction and Building Materials*, 53, 260-266.

[MAHA08] Mahaut, F., Mokéddem, S., Chateau, X., Roussel, N., & Ovarlez, G. (2008). Effect of coarse particle volume fraction on the yield stress and thixotropy of cementitious materials. *Cement and Concrete Research*, 38(11), 1276-1285.

[MAIO03] Di Maio, A. A., & Traversa, L. P. (2003). Evaluation of recycled concrete by means of non destructive tests. [Evaluación de hormigones reciclados mediante ensayos no destructivos] *Materiales De Construcción*, 53(271-272), 37-46.

[MALE10] Malešev, M., Radonjanin, V., & Marinković, S. (2010). Recycled concrete as aggregate for structural concrete production. *Sustainability*, 2(5), 1204-1225.

[MANZ13] Manzi, S., Mazzotti, C., & Bignozzi, M. C. (2013). Short and long-term behavior of structural concrete with recycled concrete aggregate. *Cement and Concrete Composites*, 37(1), 312–318.

[MARI10] Marinkovic, S., Ignjatovic, I., Radonjanin, V., & Malesev, M. (2010). Recycled aggregate concrete for structural use – an overview of technologies, properties and applications. ACES Workshop, Innovative Materials and Techniques in Concrete Construction, 10-12 October 2010, Corfu, Greece.

[MART11] Martín-Morales, M., Zamorano, M., Ruiz-Moyano, A., & Valverde-Espinosa, I. (2011). Characterization of recycled aggregates construction and demolition waste for concrete production following the Spanish structural concrete code EHE-08. *Construction and Building Materials*, 25(2), 742-748.

[MASA06] Masatao, T., Takafumi, N., Masaki, T., Manabu, K., Ippei, M., & Hironori, N. (2006). Study of the application of low - quality recycled coarse aggregate to concrete structure by surface modification treatment, in 2nd Asian Concrete Federation Conference, 2006.

[MELL99] Mellmann, G. (1999). Processed concrete rubble for the reuse as aggregate. In: Proceedings of the international seminar on exploiting waste in concrete, Dundee, Scotland, 1999, 171-178.

[MEYE09] Meyer, C. (2009). The greening of the concrete industry. *Cement and Concrete Composites*, 31(8), 601-605.

[MIRA06] Miranda, L. F. R., & Selmo, S. M. S. (2006). CDW recycled aggregate renderings: Part I – Analysis of the effect of materials finer than 75 µm on mortar properties. *Construction and Building Materials*, 20, 615-624.

[NAGA04] Nagataki, S., Gokce, A., Saeki, T., & Hisada, M. (2004). Assessment of recycling process induced damage sensitivity of recycled concrete aggregates. *Cement and Concrete Research*, 34(6), 965-971.

[NAJI11] Naji, S., Hwang, S-D., & Khayat, K. H. (2011). Robustness of Self-Consolidating Concrete Incorporating Different Viscosity-Enhancing Admixtures. *ACI Materials Journal*, 108(4), 432-438.

[NBR05] NBR (Associação Brasileira de Normas Técnicas) (2005). NBR 15.116: Recycled aggregates from construction and demolition waste: non-structural concrete – requirements (in Portuguese). Associação Brasileira de Normas Técnicas, Rio de Janeiro.

[NEAL98] Nealen, A., & Schenk, S. (1998). The influence of recycled aggregate core moisture on freshly mixed and hardened concrete properties. http:// www.b-i-m.de/public/tudmassiv/dacon13nealenschenk.htm

[NEPO12] Nepomuceno, M., Oliveira, L., & Lopes, S. M. R. (2012). Methodology for mix design of the mortar phase of self-compacting concrete using different mineral additions in binary blends of powders. *American Concrete Institute*, *ACI Special Publication*, 26, 317–326.

[NUNE06] Nunes, S., Figueiras, H., Milheiro-Oliveira, P., Coutinho, J. S., & Figueiras, J. (2006). A Methodology to Assess Robustness of SCC Mixtures. *Cement and Concrete Research*, 36, 2115-2122.

[NUNE09] Nunes, S., Milheiro-Oliveira, P., Coutinho, S., & Figueiras, J. (2009). Interaction diagrams to assess SCC mortars for different cement types. *Construction and Building Materials*, 23, 1401–1412.

[NUNE13] Nunes, S., Milheiro, P., Coutinho, J. S., & Figueiras, J. (2013). Robust SCC Mixes through Mix Design. *Journal of Materials in Civil Engineering*, 25, 183-193.

[OIKO05] Oikonomou, N. O. (2005). Recycled concrete aggregates. *Cement and Concrete Composites*, 27(2), 315-318.

[OKAM03] Okamura, H., & Ouchi, M. (2003). Self-Compacting Concrete. *Journal of Advanced Concrete Technology*, 1(1), 5-15.

[OLIV96] De Oliveira, M. B., & Vázquez, E. (1996). The influence of retained moisture in aggregates from recycling on the properties of new hardened concrete. *Waste Management*, 16(1-3), 113-117.

[ORTE10] Ortega, N. F., Moro, J.M., Meneses, R., & Aveldaño, R. R. (2010). Comportamiento dinámico de vigas de hormigón reciclado con sus armaduras corroídas. VI Congreso Internacional sobre Patología y Recuperación de Estructuras, June 2010, Argentina.

[OT06] Ot (Objectif technique) (2006) 70085 Instruction technique. Utilisation de matériaux de construction minéraux secondaires dans la construction d'abris (in French). Ot, Switzerland, 2006.

[OTSU03] Otsuki, N., Miyazato, S., & Yodsudjai, W. (2003). Influence of recycled aggregate on interfacial transition zone, strength, chloride penetration and carbonation of concrete. *Journal of Materials in Civil Engineering*, 15(5), 443-451.

[OUCH98] Ouchi, M., Hibino, M., Ozawa, K., & Okamura, H. (1998). A rational mix-design method for mortar in self-compacting concrete. Proceedings of the sixth East-Asia-Pacific Conference on Structural Engineering and Construction, Taiwan, 1307–1312.

[PACI15] Pacios-Álvarez, A., Alonso-Alonso, M. C., Dehn, F., & König, A. (2015). Rheology of self-compacting mortars with sustainable binders. IV Congresso Ibero-americano sobre Betão Auto-compactável – BAC2015, 6-7 July 2015, Porto.

[PADM09] Padmini, A. K., Ramamurthy, K., & Mathews, M. S. (2009). Influence of parent concrete on the properties of recycled aggregate concrete. *Construction and Building Materials*, 23(2), 829-836.

[PAIN11] Paine, K. A., Dhir, R. K., Halliday, J. E., Zheng, L., Collery, D. J., & Rai, H. S. (2011). Use of recycled and secondary aggregates in concrete: engineering and environmental considerations. *In*: Newlands, M. D. & Dhir, R. K., eds. *Concrete for High Performance Sustainable Infrastructure*. Mumbai: Shroff Publishers and Distributors, 77-86.

[PAIN10a] Paine, K. A., & Dhir, R. K. (2010). Recycled aggregates in concrete: a performance related approach. *Magazine of Concrete Research*, 62 (7), pp. 519-530.

[PAIN10b] Paine, K. A. (2010). Recycled aggregates for concrete: Production, properties and characteristics. *The Masterbuilder*, 12 (3), 118-124.

[PAND13] Panda, K. C., & Bal, P. K. (2013). Properties of self-compacting concrete using recycled coarse aggregate. *Procedia Engineering*, 51, 159-164.

[PEDR14a] Pedro, D., De Brito, J., & Evangelista, L. (2014). Influence of the use of recycled concrete aggregates from different sources on structural concrete. *Construction and Building Materials*, 71, 141-151.

[PEDR14b] Pedro, D., de Brito, J., & Evangelista, L. (2014). Performance of concrete made with aggregates recycled from precasting industry waste: influence of the crushing process. *Materials and Structures*, 48(12), 3965–3978.

[PELU09] Pelufo, M. J., Domingo, A., Ulloa, V. A., & Vergara, N. N. (2009). Analysis of moisture state of recycled coarse aggregate and its influence on compression strength of the concrete. Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2009, Valencia.

[PEPE16] Pepe, M., Toledo-Filho, R. D., Koenders, E. A. B., & Martinelli, E. (2016). A novel mix design methodology for Recycled Aggregate Concrete. *Construction and Building Materials*, 122, 362-372.

[PERE10] Pérez-Ordóñez, J. L. (2010). Metodología para orientar procesos de extracción de conocimiento basados en Computación Evolutiva. Aplicación al desarrollo de modelos y formulaciones en el ámbito del hormigón estructural. PhD Dissertation, Department of Information and Communication Technologies, University of A Coruña, Spain.

[PERE12] Pérez, J. L., Cladera, A., Rabuñal, J. R., & Martínez-Abella, F. (2012). Optimization of existing equations using a new Genetic Programming algorithm: Application to the shear strength of reinforced concrete beams. *Advances in Engineering Software*, 50, 82-96.

[PERE13] Pereira-de-Oliveira, L. A., Nepomuceno, M., & Rangel, M. (2013). An eco-friendly self-compacting concrete with recycled coarse aggregates. *Informes de la Construcción*, 65(EXTRA-1), 31-41.

[PERE14] Pereira-de-Oliveira, L. A., Nepomuceno, M. C. S., Castro-Gomes, J. P., & Vila, M. F. C. (2014). Permeability properties of self-compacting concrete with coarse recycled aggregates. *Construction and Building Materials*, 51, 113-120.

[PETI07] Petit, J.Y., Wirquin, E., Vanhove, Y., & Khayat, K. (2007). Yield stress and viscosity equations for mortars and self-consolidating concrete. *Cement and Concrete Research*, 37, 655–670.

[POON04a] Poon, C. S., Shui, Z. H., & Lam, L. (2004). Effect of microstructure of ITZ on compressive strength of concrete prepared with recycled aggregates. *Construction and Building Materials*, 18(6), 461-468.

[POON04b] Poon, C. S., Shui, Z. H., Lam, L., Fok, H., & Kou, S. C. (2004). Influence of moisture states of natural and recycled aggregates on the slump and compressive strength of concrete. *Cement and Concrete Research*, 34(1), 31-36.

[POON07] Poon, C. S., Kou, S. C., & Lam, L. (2007). Influence of recycled aggregate on slump and bleeding of fresh concrete. *Materials and Structures*, 40(9), 981-988.

[PUER05] Puertas, F., Santos, H., Palacios, M., & Martínez-Ramírez, S. (2005). Polycarboxylate superplasticiser admixtures: effect on hydration, microstructure and rheological behaviour in cement pastes. *Advances in Cement Research*, 17(2), 77-89.

[PUER14] Puertas, F., Varga, C., & Alonso, M. M. (2014). Rheology of alkali-activated slag pastes. Effect of the nature and concentration of the activating solution. *Cement and Concrete Composites*, 53, 279-288.

[QUAN10] Quanji, Z. (2010). Thixotropic behavior of cement-based materials: effect of clay and cement types. PhD Dissertation, Iowa State University, Ames, Iowa.

[QUIR03] Quiroga, P. N., & Fowler, D. W. (2003). The effects of aggregates characteristics on the performance of Portland cement concrete (Research Report ICAR 104-1F). International Center for Aggregates Research, Austin, TX.

[RAHA07] Rahal, K. (2007). Mechanical properties of concrete with recycled coarse aggregate. *Building and Environment,* 42(1), 407-415.

[RAHM14] Rahman, M. K., Baluch, M. H., & Malik, M. A. (2014). Thixotropic behavior of self-compacting concrete with different mineral admixtures. *Construction and Building Materials*, 50, 710-717.

[RAVI13] Ravindrarajah, R. S. (2013). High-strength self-compacting concrete for sustainable construction. *From Materials to Structures: Advancement through Innovation* – Samali, Attard & Song (Eds).

[RAVI85] Ravindrarajah Sri, R., & Tam, C. T. (1985). Properties of concrete made with crushed concrete as coarse aggregate. *Magazine of Concrete Research*, 37(130), 29-38.

[RAVI87] Ravindrarajah Sri, R., Loo, Y. H., & Tam, C. T. (1987). Recycled concrete as fine and coarse aggregates in concrete. *Magazine of Concrete Research*, 39(141), 214-220.

[RC-08] RC-08. Spanish Instruction for cements reception. Ministry of Public Works, 2009 (in Spanish).

[RIGU09] Rigueira, J. W., García-Taengua, E., & Serna-Ros, P. (2009). Self- Consolidating Concrete in Continuous Production Regarding Fresh and Hardened State Properties. *ACI Materials Journal*, 106(3), 301-307.

[RILEM94] RILEM (International Union of Testing and Research Laboratories for Materials and Structures) (1994). Specifications for Concrete with Recycled Aggregates. *Materials and Structures*, 27, 557-559.

[ROUS05] Roussel, N., Stefani, C., & Leroy, R. (2005). From mini-cone test to Abrams cone test: measurement of cement-based materials yield stress using slump tests. *Cement and Concrete Research*, 35, 817-822.

[ROUS06a] Roussel, N. (2006). A thixotropy model for fresh fluid concretes: Theory, validation and applications. *Cement and Concrete Research*, 36, 1797-1806.

[ROUS06b] Roussel, N. (2006). Correlation between yield stress and slump: Comparison between numerical simulations and concrete rheometers results. *Materials and Structures*, 39, 501–509.

[ROUS06c] Nguyen, T. L. H., Roussel, N., & Coussot, P. (2006). Correlation between L-box test and rheological parameters of a homogeneous yield stress fluid. *Cement and Concrete Research*, 36, 1789-1796.

[ROUS06d] Roussel, N. (2006). A theoretical frame to study stability of fresh concrete. *Materials and Structures*, 39, 81-91.

[ROUS07] Roussel, N. (2007). Rheology of fresh concrete: from measurements to predictions of casting processes. *Materials and Structures*, 40(10), 1001-1012.

[ROUS08] Roussel, N., & Cussigh, F. (2008). Distinct-layer casting of SCC: The mechanical consequences of thixotropy. *Cement and Concrete Research*, 38, 624-632.

[ROUS09] Roussel, N. (2009). From Rheology of Fresh Concrete to Casting Processes. *Concrete International*, March 2009, 48-52.

[ROUS10] Roussel, N., Lemaître, A., Flatt, R. J., & Coussot, P. (2010). Steady state flow of cement suspensions: A micromechanical state of the art. *Cement and Concrete Research*, 40, 77-84.

[RUBI13] Rubio-Hernández, F. J., Velázquez-Navarro, J. F., & Ordóñez-Belloc, L. M. (2013). Rheology of concrete: a study case based upon the use of the concrete equivalent mortar. *Materials and Structures*, 46(4), 587-605.

[RÜHL92] Rühl, M. (1992). Water Absorption Capacity of Recycled Demolition Rubbish. http://www.b-i-m.de/public/tudmassiv/dacon97ruehl.htm

[RYU02] Ryu, J. S. (2002). An experimental study on the effect of recycled aggregate on concrete properties. *Magazine of Concrete Research*, 54(1), 7-12.

[SAFI11] Safiuddin, M., Alengaram, U. J., Salam, M. A., Jumaat, M. Z., Jaafar, F. F., & Saad, H. B. (2011). Properties of high-workability concrete with recycled concrete aggregate. *Materials Research*, 14(2), 248-255.

[SAFI13] Safiuddin, M., Alengaram, U. J., Rahman, M. M., Salam, M. A., & Jumaat, M. Z. (2013). Use of recycled concrete aggregate in concrete: a review. *Journal of Civil Engineering and Management*, 19(6), 796-810.

[SAGO01] Sagoe-Crentsil, K. K., Browm, T., & Taylor, A. H. (2001) Performance of concrete made with commercially produced coarse recycled concrete aggregate. *Cement and Concrete Research*, 31, 707–712.

[SAID14] Saidi, M., Ait-Medjber, F., Safi, B., & Samar, M. (2014). Recycling of Aggregates from Construction Demolition Wastes in Concrete: Study of Physical and Mechanical Properties. *International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering*, 8(12), 1307-1311.

[SANI05] Sani, D., Moriconi, G., Fava, G., & Corinaldesi, V. (2005). Leaching and mechanical behaviour of concrete manufactured with recycled aggregates. *Waste Management*, 25, 177-182.

[SCHU05] De Schutter, G. (2005). Guidelines for testing fresh self-compacting concrete. September 2005, 23 pp.

[SCHW00] Schwartzentruber, A., & Catherine, C. (2000). Method of the concrete equivalent mortar (CEM) — A new tool to design concrete containing admixture. *Materials and Structures*, 33, 475–482.

[SDGs15] United Nations, Sustainable Development Goals (SDGs): 17 goals to transform our world, 2015. [Online]. Available: http://www.un.org/sustainabledevelopment/sustainable-development-goals/ (accessed 20.01.16).

[SEAR14] Seara-Paz, S., González-Fonteboa, B., Eiras-López, J., & Herrador, M. F. (2014). Bond behaviour between steel reinforcement and recycled concrete. *Materials and Structures,* 47(1-2), 323-334.

[SEAR15] Seara-Paz, S. (2015). Effect of long-term deformations in structural flexural performance and bond behaviour analysis of recycled concrete (in Spanish). PhD Dissertation, University of A Coruña, Spain.

[SEAR16] Seara-Paz, S., González-Fonteboa, B., Martínez-Abella, F., & González-Taboada, I. (2016). Time-dependent behaviour of structural concrete made with recycled coarse aggregates. Creep and shrinkage. *Construction and Building Materials*, 122, 95-109.

[SEÑA16] Señas, L., Priano, C., & Marfil, S. (2016). Influence of recycled aggregates on properties of self-consolidating concretes. *Construction and Building Materials*, 113, 498–505.

[SEO14] Seo, D. S., & Choi, H. B. (2014). Effects of the old cement mortar attached to the recycled aggregate surface on the bond characteristics between aggregate and cement mortar. *Construction and Building Materials*, 59 (2014), 72-77.

[SHEN14] Effects of Aggregate Properties and Concrete Rheology on Stability Robustness of Self-Consolidating Concrete. *Journal of Materials in Civil Engineering*, 27(5).

[SHEN15] Shen, L., Jovein, H. B., Shen, S., & Li, M. (2015). Effects of Aggregate Properties and Concrete Rheology on Stability Robustness of Self-Consolidating Concrete. *Journal of Materials in Civil Engineering*, 27(5).

[SHI15] Shi, C., Wu, Z., Lv, K., & Wu, L. (2015). A review on mixture design methods for self-compacting concrete. *Construction and Building Materials*, 84, 387–398.

[SIEG88] Siegel, S., & Castellan, N. J. (1988). Non Parametric Statistics for the Behavioral Sciences, second edition, McGraw-Hill, New York, 270-365.

[SILV14] Silva, R. V., De Brito, J., & Dhir, R. K. (2014). Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. *Construction and Building Materials,* 65, 201-217.

[SILV15a] Silva, R. V., De Brito, J., & Dhir, R. K. (2015). The influence of the use of recycled aggregates on the compressive strength of concrete: A review. *European Journal of Environmental and Civil Engineering,* 19(7), 825-849.

[SILV15b] Silva, R. V., De Brito, J., & Dhir, R. K. (2015). Tensile strength behaviour of recycled aggregate concrete. *Construction and Building Materials,* 83, 108-118.

[SILV15c] Silva, R. V., de Brito, J., & Dhir, R. K. (2015). Prediction of the shrinkage behavior of recycled aggregate concrete: A review. *Construction and Building Materials*, 77, 327–339.

[SILV16] Silva, Y. F., Robayo, R. A., Mattey, P. E., & Delvasto, S. (2016). Properties of self-compacting concrete on fresh and hardened with residue of masonry and recycled concrete. *Construction and Building Materials*, 124, 639-644.

[SPAE13] Spaeth, V., & Djerbi Tegguer, A. (2013). Improvement of recycled concrete aggregate properties by polymer treatments. *International Journal of Sustainable Built Environment,* 2, 143-152.

[SPEA04] Spearman, C. (1904). The proof and measurement of association between two things. *American Journal of Psychology*, 15, 72-101.

[SUCI16] Sucic, A., & Lotfy, A. (2016). Effect of new paste volume on performance of structural concrete using coarse and granular recycled concrete aggregate of controlled quality. *Construction and Building Materials*, 108, 119-128.

[TAM07] Tam, V. W. Y., Tam, C. M., & Le, K. N. (2007). Removal of cement mortar remains from recycled aggregate using pre-soaking approaches. *Resources, Conservation and Recycling,* 50(1), 82–101.

[TAM08] Tam, V. W. Y., Wang, K., & Tam, C. M. (2008). Assessing relationships among properties of demolished concrete, recycled aggregate and recycled aggregate concrete using regression analysis. *Journal of Hazardous Materials,* 152, 703-714.

[TAM15] Tam, V. W. Y., Kotrayothar, D., & Xiao, J. (2015). Long-term deformation behaviour of recycled aggregate concrete. *Construction and Building Materials*, 100, 262–272.

[TANG10] Tangchirapat, W., Buranasing, R., & Jaturapitakkul, C. (2010). Use of high fineness of fly ash to improve properties of recycled aggregate concrete. *Journal of Materials in Civil Engineering*, 22(6), 565-571.

[TANG13] Tang, W. (2013). Fresh Properties of Self-compacting Concrete with Coarse Recycled Aggregate. *Advanced Materials Research,* 602-604, 938-942.

[TANG16] Tang, W. C., Ryan, P. C., Cui, H. Z., & Liao, W. (2016). Properties of Self-Compacting Concrete with Recycled Coarse Aggregate. *Advances in Materials Science and Engineering*, 2016, article ID 2761294, 11 pp.

[TATT83] Tattersall, G. H., & Banfill, P. F. G. (1983). The Rheology of Fresh Concrete. Pitman, London.

[TEST04] Measurement of properties of fresh self-compacting concrete. Final Report. European Research Project: TESTING-SCC, 2001-2004.

[THOM13] Thomas, C., Setién, J., Polanco, J. A., Alaejos, P., & Sánchez de Juan, M. (2013). Durability of recycled aggregate concrete. *Construction and Building Materials*, 40, 1054-1065.

[THRA10] Thrane, L. N., Pade, C., & Nielsen, C. V. (2010). Determination of Rheology of Self-Consolidating Concrete Using the 4C-Rheometer and How to Make Use of the Results. *Journal of ASTM International*, 7(1), 1-10.

[TOUT06] Toutou, Z. & Roussel, N. (2006). Multi scale experimental study of concrete rheology: From water scale to gravel scale. *Materials and Structures*, 39, 189-199.

[TROC13] Trocoli, A., Batista, M., & De Jesus, K. (2013). Prediction of compressive strength of concrete containing construction and demolition waste using artificial neural networks. *Construction and Building Materials,* 38, 717-722.

[TUYA14] Tuyan, M., Mardani-Aghabaglou, A., & Ramyar, K. (2014). Freeze–thaw resistance, mechanical and transport properties of self-consolidating concrete incorporating coarse recycled concrete aggregate. *Materials & Design*, 53, 983-991.

[URBA15] Urban, M. (2015). The new conception of self-compacting concrete composition design: theoretical background, evaluation, presentation of procedure and examples of usage. *Materials and Structures*, 48, 1321–1341.

[VIEI11] Vieira, J. P. B., Correia, J. R., & De Brito, J. (2011). Post-fire residual mechanical properties of concrete made with recycled concrete coarse aggregates. *Cement and Concrete Research*, 41(5), 533-541.

[VIKA05] Vikan, H. (2005). Rheology and reactivity of cementitious binders with plasticizers. Norwegian University of Science and Technology.

[VILA09] Vilanova-Fernández, A. (2009). Influence of the composition and the use of different types of cement and additions in the properties of self-compacting concrete (in Spanish). PhD Dissertation, Polytechnic University of Madrid, Spain.

[VILL08] Villagrán-Zaccardi, Y. A., Zega, C. J., & Di Maio, Á. A. (2008). Chloride penetration and binding in recycled concrete. *Journal of Materials in Civil Engineering*, 20(6), 449-455.

[VINC94] Vincke, J., & Rousseau, E. (1994). Recycling of construction and demolition waste in Belgium: Actual situation and future evolution. Demolition and Reuse of Concrete and Masonry, Proceedings of the Third International RILEM Symposium, Edited by Lauritzen, E. K., Published by E&FN Spon, 2-6 Boundary Row, London SE 1 8HN, First Edition, 57-69.

[WALL06] Wallevik, O. H. (2006). Concrete around the world. 31st Conference on *Our World in Concrete & Structures*, 16 - 17 August 2006, Singapore.

[WALL11] Wallevick, O. H., & Wallevick, J. E. (2011). Rheology as a tool in concrete science: The use of rheographs and workability boxes. *Cement and Concrete Research*, 41, 1279–1288.

[WALL15] Wallevik, O. H., Feys, D., Wallevik, J. E., & Khayat, K. H. (2015). Avoiding inaccurate interpretations of rheological measurements for cement-based materials. *Cement and Concrete Research*, 78, 100-109.

[WALL88] Wallevik, O. H., & Gjørv, O. E. (1988). Rheology of Fresh Concrete. In *Advances in Cement Manufacture and Use*, 133-134. Eng. Found. Conf., Potosi, Michigan.

[WBTC02] WBTC (2002) WBTC No. 12/2002: Specifications Facilitating the Use of Recycled Aggregates. Works Bureau Technical Circular, Hong-Kong.

[WÜST03] Wüstholz, T. (2003). Fresh properties of self-compacting concrete (SCC). *Otto-Graf-Journal*, 14, 179-188.

[WÜST05] Wüstholz, T. (2005). A model approach to describe the fresh properties of self-compacting concrete (SCC). *Otto-Graf-Journal*, 16, 79-93.

[XIAO05] Xiao, J., Li, J., & Zhang, C. (2005). Mechanical properties of recycled aggregate concrete under uniaxial loading. *Cement and Concrete Research*, 35, 1187-1194.

[XIAO06] Xiao, J. Zh., Li, J. B., & Zhang, Ch. (2006). On relationships between the mechanical properties of recycled aggregate concrete: An overview. *Materials and Structures*, 39, 655-664.

[XIAO12] Xiao, J., Li, W., Fan, Y., & Huang, X. (2012). An overview of study on recycled aggregate concrete in China (1996–2011). *Construction and Building Materials*, 31, 364–383.

[XIAO13a] Xiao, J., Lu, D., & Ying, J. (2013). Durability of Recycled Aggregate Concrete: An Overview. *Journal of Advanced Concrete Technology*, 11(12), 347–359.

[XIAO13b] Xiao, J., Li, W., Sun, Z., Lange, D. A., & Shah, S. P. (2013). Properties of interfacial transition zones in recycled aggregate concrete tested by nanoindentation. *Cement and Concrete Composites,* 37, 276-292.

[XIAO14] Xiao, J., Li, L., Tam, V. W. Y., & Li, H. (2014). The state of the art regarding the long-term properties of recycled aggregate concrete. *Structural Concrete*, 15(1), 3-12.

[YAMM08] Yammine, J., Chaouche, M., Guerinet, M., Moranville, M., & Roussel, N. (2008). From ordinary rhelogy concrete to self-compacting concrete: A transition between frictional and hydrodynamic interactions. *Cement and Concrete Research*, 38(7), 890-896.

[YILD15] Yildirim, S. T., Meyer, C., & Herfellner, S. (2015). Effects of internal curing on the strength, drying shrinkage and freeze-thaw resistance of concrete containing recycled concrete aggregates. *Construction and Building Materials,* 91, 288-296.

[YOUN13] Younis, K. H., & Pilakoutas, K. (2013). Strength prediction model and methods for improving recycled aggregate concrete. *Construction and Building Materials,* 49, 688-701.

[YU14] Yu, J., Gong, J., Zou, J., & Yang, W. (2014). Study on properties of self-compacting concrete prepared with coarse recycled concrete aggregate. *Applied Mechanics and Materials*, 638-640, 1494-1498.

[YUAN12] Yuan, Y., Takao, U., & Yu, C. (2012). SCC Produced with Recycled Concrete Aggregates. *Advanced Materials Research*, 512-515, 2986-2989.

[ZAHA03] Zaharieva, R., Buyle-Bodin, F., Skoczylas, F., & Wirquin, E. (2003). Assessment of the surface permeation properties of recycled aggregate concrete. *Cement and Concrete Composites*, 25(2), 223-232.

[ZEGA10] Zega, C. J., Villagrán-Zaccardi, Y. A., & Di Maio, A. A. (2010). Effect of natural coarse aggregate type on the physical and mechanical properties of recycled coarse aggregates. *Materials and Structures*, 43, 195-202.

[ZHAN07] Zhang, X., Deng, S., & Qin, Y. (2007). Additional adsorbed water in recycled concrete. *Journal of Central South University of Technology* (English Edition), 14(1 SUPPL.), 449-453.

[ZHAN16] Zhang, J., An, X., & Nie, D. (2016). Effect of fine aggregate characteristics on the thresholds of self-compacting paste rheological properties. *Construction and Building Materials*, 116, 355-365.

[ZILC01] Zilch, Z., & Roos, F. (2001). An equation to estimate the modulus of elasticity of concrete with recycled aggregates. *Civil Engineering*, 76, 187-191.

REFERENCES – RECYCLED CONCRETE AGGREGATE DATABASE

[1] Abbas, A., Fathifazl, G., Fournier, B., Isgor, O. B., Zavadil, R., Razaqpur, A. G., & Foo, S. (2009). Quantification of the residual mortar content in recycled concrete aggregates by image analysis. *Materials Characterization*, 60(7), 716-728.

[2] Agrela, F., Sánchez de Juan, M., Ayuso, J., Geraldes, V. L., & Jiménez, J. R. (2011). Limiting properties in the characterisation of mixed recycled aggregates for use in the manufacture of concrete. *Construction and Building Materials*, 25(10), 3950-3955.

[3] Ajdukiewicz, A., & Kliszczewicz, A. (2002). Influence of recycled aggregates on mechanical properties of HS/HPC. *Cement and Concrete Composites*, 24(2), 269-279.

[4] Akbarnezhad, A., Ong, K. C. G., Tam, C. T., & Zhang, M. H. (2013). Effects of the parent concrete properties and crushing procedure on the properties of coarse recycled concrete aggregates. *Journal of Materials in Civil Engineering,* 25(12), 1795-1802.

[5] Akbarnezhad, A., Ong, K. C. G., Zhang, M. H., Tam, C. T., & Foo, T. W. J. (2011). Microwave-assisted beneficiation of recycled concrete aggregates. *Construction and Building Materials*, 25(8), 3469-3479.

[6] Angulo, S. C., Carrijo, P. M., Figueiredo, A. D., Chaves, A. P., & John, V. M. (2010). On the classification of mixed construction and demolition waste aggregate by porosity and its

impact on the mechanical performance of concrete. *Materials and Structures*, 43(4), 519-528.

[7] Ann, K. Y., Moon, H. Y., Kim, Y. B., & Ryou, J. (2008). Durability of recycled aggregate concrete using pozzolanic materials. *Waste Management*, 28(6), 993-999.

[8] Bairagi, N. K., Ravande, K., & Pareek, V. K. (1993). Behaviour of concrete with different proportions of natural and recycled aggregates. *Resources, Conservation and Recycling*, 9(1-2), 109-126.

[9] Bairagi, N. K., Vidyadhara, H. S., & Ravande, K. (1990). Mix design procedure for recycled aggregate concrete. *Construction and Building Materials*, 4(4), 188-193.

[10] Barbudo, A., De Brito, J., Evangelista, L., Bravo, M., & Agrela, F. (2013). Influence of water-reducing admixtures on the mechanical performance of recycled concrete. *Journal of Cleaner Production,* 59, 93-98.

[11] Barra, M., & Vázquez, E. (1997). Particularidades do proceso de carbonatação em concretos de agregado reciclado. IV Congreso Iberoamericano de Patología de las Construcciones, VI Congreso de Control y Calidad, Octubre 1997, Brasil.

[12] Batayneh, M., Marie, I., & Asi, I. (2007). Use of selected waste materials in concrete mixes. *Waste Management*, 27(12), 1870-1876.

[13] Belin, P., Habert, G., Thiery, M., & Roussel, N. (2014). Cement paste content and water absorption of recycled concrete coarse aggregates. *Materials and Structures,* 47(9), 1451-1465.

[14] Beltrán, M. G., Barbudo, A., Agrela, F., Galvín, A. P., & Jiménez, J. R. (2014). Effect of cement addition on the properties of recycled concretes to reach control concretes strengths. *Journal of Cleaner Production,* 79, 124-133.

[15] Berndt, M. L. (2009). Properties of sustainable concrete containing fly ash, slag and recycled concrete aggregate. *Construction and Building Materials*, 23(7), 2606-2613.

[16] Bhikshma, V., & Kishore, R. (2010). Development of stress - strain curves for recycled aggregate concrete. *Asian Journal of Civil Engineering*, 11(2), 253-261.

[17] Brand, A. S., Roesler, J. R., & Salas, A. (2015). Initial moisture and mixing effects on higher quality recycled coarse aggregate concrete. *Construction and Building Materials, 79*, 83-89.

[18] Butler, L., Tighe, S. L., & West, J. S. (2013). Guidelines for selection and use of coarse recycled-concrete aggregates in structural concrete. *Journal of the Transportation Research Board*, 2335, 3-12.

[19] Buyle-Bodin, F., & Hadjieva-Zaharieva, R. (2002). Influence of industrially produced recycled aggregates on flow properties of concrete. *Materials and Structures*, 35, 504-509.

[20] Cabral, A. E. B., Schalch, V., Molin, D. C. C. D., & Ribeiro, J. L. D. (2010). Mechanical properties modelling of recycled aggregate concrete. *Construction and Building Materials*, 24(4), 421-430.

[21] Castaño, J. O., Domingo, A., & Lázaro, C. (2009). A study on drying shrinkage and creep of recycled concrete aggregate. Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2009, Valencia.

[22] Casuccio, M., Torrijos, M. C., Giaccio, G., & Zerbino, R. (2008). Failure mechanism of recycled aggregate concrete. *Construction and Building Materials*, 22(7), 1500-1506.

[23] Chakradhara Rao, M., Bhattacharyya, S. K., & Barai, S. V. (2011). Behaviour of recycled aggregate concrete under drop weight impact load. *Construction and Building Materials*, 25(1), 69-80.

[24] Chakradhara Rao, M., Bhattacharyya, S. K., & Barai, S. V. (2011). Influence of field recycled coarse aggregate on properties of concrete. *Materials and Structures*, 44(1), 205-220.

[25] Chen, A., Wang, J., & Ge, Z. (2011). Experimental study on the fundamental characteristics of recycled concrete. *Advanced Materials Research*, vols. 295-297, pp. 958-961.

[26] Chen, Z., Huang, K., Zhang, X., & Xue, J. (2010). Experimental research on the flexural strength of recycled coarse aggregate concrete. In: 2010 International Conference on

Mechanic Automation and Control Engineering, 26-28 June 2010, Wuhan, China, 1041-1043.

[27] Corinaldesi, V. & Moriconi, G. (2012). Recycled aggregate concretes for structural applications: from investigation to design. *Advanced Materials Research*, 548, 209-214.

[28] Corinaldesi, V. (2011). Structural concrete prepared with coarse recycled concrete aggregate: From investigation to design. *Advances in Civil Engineering*, 2011.

[29] Corinaldesi, V., Letelier, V., & Moriconi, G. (2011). Behaviour of beam-column joints made of recycled-aggregate concrete under cyclic loading. *Construction and Building Materials*, 25(4), 1877-1882.

[30] Corinaldesi, V. (2010). Mechanical and elastic behaviour of concretes made of recycled-concrete coarse aggregates. *Construction and Building Materials*, 24(9), 1616-1620.

[31] Corinaldesi, V., & Moriconi, G. (2010). Recycling of rubble from building demolition for low-shrinkage concretes. *Waste Management*, 30(4), 655-659.

[32] Corinaldesi, V., & Moriconi, G. (2009). Behaviour of cementitious mortars containing different kinds of recycled aggregate. *Construction and Building Materials*, 23(1), 289-294.

[33] Corinaldesi, V., & Moriconi, G. (2009). Influence of mineral additions on the performance of 100% recycled aggregate concrete. *Construction and Building Materials*, 23(8), 2869-2876.

[34] Courard, L., Michel, F., & Delhez, P. (2010). Use of concrete road recycled aggregates for roller compacted concrete. *Construction and Building Materials*, 24(3), 390-395.

[35] Cui, H. Z., Shi, X., Memon, S. A., Xing, F., & Tang, W. (2014). Experimental study on the influence of water absorption of recycled coarse aggregates on properties of the resulting concretes. *Journal of Materials in Civil Engineering,* 27(4).

[36] De Juan, M. S. (2005). Estudio sobre la utilización de árido reciclado para la fabricación de Hormigón Estructural. PhD Dissertation, Polytechnic University of Madrid, Spain.

[37] De Oliveira, M. B., & Vazquez, E. (1996). The influence of retained moisture in aggregates from recycling on the properties of new hardened concrete. *Waste Management*, 16(1-3), 113-117.

[38] Debieb, F., Courard, L., Kenai, S., & Degeimbre, R. (2010). Mechanical and durability properties of concrete using contaminated recycled aggregates. *Cement and Concrete Composites*, 32(6), 421-426.

[39] Debieb, F., Courard, L., Kenai, S., & Degeimbre, R. (2009). Roller compacted concrete with contaminated recycled aggregates. *Construction and Building Materials*, 23(11), 3382-3387.

[40] Di Maio, A. A., & Traversa, L. P. (2003). Evaluation of recycled concrete by means of non destructive tests. [Evaluación de hormigones reciclados mediante ensayos no destructivos] *Materiales De Construcción*, 53(271-272), 37-46.

[41] Djerbi Tegguer, A. (2012). Determining the water absorption of recycled aggregates utilizing hydrostatic weighing approach. *Construction and Building Materials,* 27(1), 112-116.

[42] Domingo-Cabo, A., Lázaro, C., López-Gayarre, F., Serrano-López, M. A., Serna, P., & Castaño-Tabares, J. O. (2009). Creep and shrinkage of recycled aggregate concrete. *Construction and Building Materials*, 23(7), 2545-2553.

[43] Duan, Z. H., & Poon, C. S. (2014). Properties of recycled aggregate concrete made with recycled aggregates with different amounts of old adhered mortars. *Materials and Design,* 58, 19-29.

[44] Eguchi, K., Teranishi, K., Nakagome, A., Kishimoto, H., Shinozaki, K., & Narikawa, M. (2007). Application of recycled coarse aggregate by mixture to concrete construction. *Construction and Building Materials*, 21(7), 1542-1551.

[45] Etxeberria, M., Marí, A. R., & Vázquez, E. (2007). Recycled aggregate concrete as structural material. *Materials and Structures*, 40(5), 529-541.

[46] Etxeberria, M., Vázquez, E., Marí, A., & Barra, M. (2007). Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete. *Cement and Concrete Research*, 37(5), 735-742.

[47] Evangelista, L., & de Brito, J. (2007). Mechanical behaviour of concrete made with fine recycled concrete aggregates. *Cement and Concrete Composites*, 29(5), 397-401.

[48] Faleschini, F., Jiménez, C., Barra, M., Aponte, D., Vázquez, E., & Pellegrino, C. (2014). Rheology of fresh concretes with recycled aggregates. *Construction and Building Materials,* 73, 407-416.

[49] Ferreira, L., De Brito, J., & Barra, M. (2011). Influence of the pre-saturation of recycled coarse concrete aggregates on concrete properties. *Magazine of Concrete Research*, 63(8), 617-627.

[50] Folino, P., & Xargay, H. (2014). Recycled aggregate concrete - mechanical behavior under uniaxial and triaxial compression. *Construction and Building Materials,* 56, 21-31.

[51] Fonseca, N., de Brito, J., & Evangelista, L. (2011). The influence of curing conditions on the mechanical performance of concrete made with recycled concrete waste. *Cement and Concrete Composites*, 33(6), 637-643.

[52] Garg, A., Koster, G., & Rühl, M. (1998). Implementation of long term measurements at a building made of concrete with aggregate derived from concrete rubble. http://www.b-i-m.de/public/tudmassiv/dacon13gargkoster.htm

[53] Gokce, A., Nagataki, S., Saeki, T., & Hisada, M. (2011). Identification of frost-susceptible recycled concrete aggregates for durability of concrete. *Construction and Building Materials*, 25(5), 2426-2431.

[54] Gomes, M., de Brito, J., & Bravo, M. (2014). Mechanical performance of structural concrete with the incorporation of coarse recycled concrete and ceramic aggregates. *Journal of Materials in Civil Engineering,* 26(10).

[55] Gómez-Soberón, J. M. V. (2002). Porosity of recycled concrete with substitution of recycled concrete aggregate: An experimental study. *Cement and Concrete Research*, 32(8), 1301-1311.

[56] González, A., & Etxeberria, M. (2014). Experimental analysis of properties of high performance recycled aggregate concrete. *Construction and Building Materials,* 52, 227-235.

[57] González-Fonteboa, B., Martínez-Abella, F., Herrador, M. F., & Seara-Paz, S. (2012). Structural recycled concrete: Behaviour under low loading rate. *Construction and Building Materials,* 28(1), 111-116.

[58] González, B., Martínez, F., Carro, D., & Seara, S. (2011). Stress-strain relationship in axial compression for concrete using recycled saturated coarse aggregate. *Construction and Building Materials*, 25(5), 2335-2342.

[59] González-Fonteboa, B., & Martínez-Abella, F. (2005). Recycled aggregates concrete: Aggregate and mix properties [Hormigones con áridos reciclados: Estudio de propiedades de los áridos y de las mezclas]. *Materiales De Construcción*, 55(279), 53-66.

[60] Grdic, Z. J., Toplicic-Curcic, G. A., Despotovic, I. M., & Ristic, N. S. (2010). Properties of self-compacting concrete prepared with coarse recycled concrete aggregate. *Construction and Building Materials*, 24(7), 1129-1133.

[61] Grübl, P., & Nealen, A. (1998). Construction of an office building using concrete made from recycled demolition material. *Aus Darmstadt Concrete*, 13.

[62] Hansen, T. C., & Narud, H. (1983). Strength of recycled concrete made from crushed concrete coarse aggregate. *Concrete International*, 5(1), 79-83.

[63] Hincapié Henao, Á. M., & Aguja López, E. A. (2003). Agregado reciclado para morteros Universidad EAFIT, 39(132), 76-89.

[64] Ho, N. Y., Lee, Y. P. K., Lim, W. F., Zayed, T., Chew, K. C., Low, G. L., et al. (2013). Efficient utilization of recycled concrete aggregate in structural concrete. *Journal of Materials in Civil Engineering,* 25(3), 318-327.

[65] Ismail, S., & Ramli, M. (2013). Engineering properties of treated recycled concrete aggregate (RCA) for structural applications. *Construction and Building Materials*, 44, 464-476.

[66] Jiménez, C., Aponte, D., Vázquez, E., Barra, M., & Valls, S. (2013). Equivalent mortar volume (EMV) method for proportioning recycled aggregate concrete: Validation under the Spanish context and its adaptation to Bolomey methodology for concrete proportioning [Diseño de mezclas de hormigón reciclado mediante el método Volumen de Mortero Equivalente (EMV): Validación bajo el contexto español y su adaptación al método de diseño de Bolomey]. *Materiales De Construcción,* 63(311), 341-360.

[67] Jo, B., Park, S., & Park, J. (2008). Mechanical properties of polymer concrete made with recycled PET and recycled concrete aggregates. *Construction and Building Materials*, 22(12), 2281-2291.

[68] Kalaiarasu, S. M., & Subramanian, K. (2006). Properties of recycled aggregate concrete with silica fume. *Journal of Applied Sciences*, 6(14), 2956-2958.

[69] Katz, A. (2004). Treatments for the improvement of recycled aggregate. *Journal of Materials in Civil Engineering*, 16(6), 597-603.

[70] Katz, A. (2003). Properties of concrete made with recycled aggregate from partially hydrated old concrete. *Cement and Concrete Research*, 33(5), 703-711.

[71] Kebaïli, O., Mouret, M., Arabia, N., & Cassagnabere, F. (2015). Adverse effect of the mass substitution of natural aggregates by air-dried recycled concrete aggregates on the self-compacting ability of concrete: Evidence and analysis through an example. *Journal of Cleaner Production,* 87(1), 752-761.

[72] Khatib, J. M. (2005). Properties of concrete incorporating fine recycled aggregate. *Cement and Concrete Research*, 35(4), 763-769.

[73] Khoshkenari, A. G., Shafigh, P., Moghimi, M., & Mahmud, H. B. (2014). The role of 0-2mm fine recycled concrete aggregate on the compressive and splitting tensile strengths of recycled concrete aggregate concrete. *Materials and Design,* 64, 345-354.

[74] Kim, K., Shin, M., & Cha, S. (2013). Combined effects of recycled aggregate and fly ash towards concrete sustainability. *Construction and Building Materials,* 48, 499-507.

[75] Kishore, R. (2007). Influence of recycled aggregate on flexural behaviour of reinforced concrete beams. http://www.claisse.info/supplementary%20papers/kishor_full_text.pdf

[76] Knaack, A. M. & Kurama, Y. C. (2012). Rheological and mechanical behavior of concrete mixtures with recycled concrete aggregates. Proceedings of the ASCE Structures Congress, Chicago, Illinois.

[77] Kong, D., Lei, T., Zheng, J., Ma, C., Jiang, J., & Jiang, J. (2010). Effect and mechanism of surface-coating pozzolanics materials around aggregate on properties and ITZ microstructure of recycled aggregate concrete. *Construction and Building Materials*, 24(5), 701-708.

[78] Kou, S., & Poon, C. (2015). Effect of the quality of parent concrete on the properties of high performance recycled aggregate concrete. *Construction and Building Materials,* 77, 501-508.

[79] Kou, S., & Poon, C. (2013). Long-term mechanical and durability properties of recycled aggregate concrete prepared with the incorporation of fly ash. *Cement and Concrete Composites,* 37(1), 12-19.

[80] Kou, S. C., & Poon, C. S. (2012). Enhancing the durability properties of concrete prepared with coarse recycled aggregate. *Construction and Building Materials,* 35, 69-76.

[81] Kou, S., Poon, C., & Etxeberria, M. (2011). Influence of recycled aggregates on long term mechanical properties and pore size distribution of concrete. *Cement and Concrete Composites*, 33(2), 286-291.

[82] Kou, S., & Poon, C. (2010). Properties of concrete prepared with PVA-impregnated recycled concrete aggregates. *Cement and Concrete Composites*, 32(8), 649-654.

[83] Kou, S. C., & Poon, C. S. (2009). Properties of self-compacting concrete prepared with coarse and fine recycled concrete aggregates. *Cement and Concrete Composites*, 31(9), 622-627.

[84] Kou, S., & Poon, C. (2009). Properties of concrete prepared with crushed fine stone, furnace bottom ash and fine recycled aggregate as fine aggregates. *Construction and Building Materials*, 23(8), 2877-2886.

[85] Kou, S. C., Poon, C. S., & Chan, D. (2008). Influence of fly ash as a cement addition on the hardened properties of recycled aggregate concrete. *Materials and Structures*, 41(7), 1191-1201.

[86] Kou, S. C., Poon, C. S., & Dixon, C. (2007). Influence of fly ash as cement replacement on the properties of recycled aggregate concrete. *Journal of Materials in Civil Engineering*, 19(9), 709-717.

[87] Leite, M. B., Figueire Do Filho, J. G. L., & Lima, P. R. L. (2013). Workability study of concretes made with recycled mortar aggregate. *Materials and Structures,* 46(10), 1765-1778.

[88] Levy, S. M., & Helene, P. (2004). Durability of recycled aggregates concrete: A safe way to sustainable development. *Cement and Concrete Research*, 34(11), 1975-1980.

[89] Li, W., Xiao, J., Sun, Z., Kawashima, S., & Shah, S. P. (2012). Interfacial transition zones in recycled aggregate concrete with different mixing approaches. *Construction and Building Materials,* 35, 1045-1055.

[90] Li, Y., Tao, J., Lei, T., & Xie, J. (2011). Experimental study on compressive strength of recycled concrete. *Advanced Materials Research*, vols. 261-263, pp. 75-78.

[91] Li, J., Xiao, H., & Zhou, Y. (2009). Influence of coating recycled aggregate surface with pozzolanic powder on properties of recycled aggregate concrete. *Construction and Building Materials*, 23(3), 1287-1291.

[92] Lima, C., Caggiano, A., Faella, C., Martinelli, E., Pepe, M., & Realfonzo, R. (2013). Physical properties and mechanical behaviour of concrete made with recycled aggregates and fly ash. *Construction and Building Materials,* 47, 547-559.

[93] Limbachiya, M., Meddah, M. S., & Ouchagour, Y. (2012). Use of recycled concrete aggregate in fly-ash concrete. *Construction and Building Materials,* 27(1), 439-449.

[94] Lin, Y., Tyan, Y., Chang, T., & Chang, C. (2004). An assessment of optimal mixture for concrete made with recycled concrete aggregates. *Cement and Concrete Research*, 34(8), 1373-1380.

[95] López Gayarre, F., López-Colina Pérez, C., Serrano López, M. A., & Domingo Cabo, A. (2014). The effect of curing conditions on the compressive strength of recycled aggregate concrete. *Construction and Building Materials,* 53, 260-266.

[96] López-Gayarre, F., Serna, P., Domingo-Cabo, A., Serrano-López, M. A., & López-Colina, C. (2009). Influence of recycled aggregate quality and proportioning criteria on recycled concrete properties. *Waste Management*, 29(12), 3022-3028.

[97] Malešev, M., Radonjanin, V., & Marinković, S. (2010). Recycled concrete as aggregate for structural concrete production. *Sustainability*, 2(5), 1204-1225.

[98] Manzi, S., Mazzotti, C., & Bignozzi, M. C. (2013). Short and long-term behavior of structural concrete with recycled concrete aggregate. *Cement and Concrete Composites,* 37(1), 312-318.

[99] Matias, D., De Brito, J., Rosa, A., & Pedro, D. (2013). Mechanical properties of concrete produced with recycled coarse aggregates - influence of the use of superplasticizers. *Construction and Building Materials,* 44, 101-109.

[100] Mefteh, H., Kebaïli, O., Oucief, H., Berredjem, L., & Arabi, N. (2013). Influence of moisture conditioning of recycled aggregates on the properties of fresh and hardened concrete. *Journal of Cleaner Production,* 54, 282-288.

[101] Miranda, L. F. R., & Selmo, S. M. S. (2006). CDW recycled aggregate renderings: Part I – analysis of the effect of materials finer than 75 µm on mortar properties. *Construction and Building Materials*, 20(9), 615-624.

[102] Morohashi, N., & Sakurada, T. (2008). An experimental study on the bond splitting strength of reinforced concrete beams with a mixture of recycled aggregate and normal aggregate. *Journal of Structural and Construction Engineering*, 73(634), 2175-2183.

[103] Nagataki, S., Gokce, A., Saeki, T., & Hisada, M. (2004). Assessment of recycling process induced damage sensitivity of recycled concrete aggregates. *Cement and Concrete Research*, 34(6), 965-971.

[104] Ortega, N. F., Moro, J.M., Meneses, R., & Aveldaño, R. R. (2010). Comportamiento dinámico de vigas de hormigón reciclado con sus armaduras corroídas. VI Congreso Internacional sobre Patología y Recuperación de Estructuras, June 2010, Argentina.

[105] Otsuki, N., Miyazato, S., & Yodsudjai, W. (2003). Influence of recycled aggregate on interfacial transition zone, strength, chloride penetration and carbonation of concrete. *Journal of Materials in Civil Engineering*, 15(5), 443-451.

[106] Padmini, A. K., Ramamurthy, K., & Mathews, M. S. (2009). Influence of parent concrete on the properties of recycled aggregate concrete. *Construction and Building Materials*, 23(2), 829-836.

[107] Park, S. B., Seo, D. S., & Lee, J. (2005). Studies on the sound absorption characteristics of porous concrete based on the content of recycled aggregate and target void ratio. *Cement and Concrete Research*, 35(9), 1846-1854.

[108] Pedro, D., De Brito, J., & Evangelista, L. (2014). Influence of the use of recycled concrete aggregates from different sources on structural concrete. *Construction and Building Materials,* 71, 141-151.

[109] Pelufo, M. J., Domingo, A., Ulloa, V. A., & Vergara, N. N. (2009). Analysis of moisture state of recycled coarse aggregate and its influence on compression strength of the concrete. Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2009, Valencia.

[110] Peng, G. F., Liu, Q. B., Guo, Z. B., Hou, Q. X., Cao, S. Q., & Zhang, J. F. (2011). Mechanical properties and permeability of recycled aggregate concrete at low water/binder ratio. *Key Engineering Materials*, 477, 16-22.

[111] Pepe, M., Toledo Filho, R. D., Koenders, E. A. B., & Martinelli, E. (2014). Alternative processing procedures for recycled aggregates in structural concrete. *Construction and Building Materials,* 69, 124-132.

[112] Pereira, P., Evangelista, L., & de Brito, J. (2012). The effect of superplasticizers on the mechanical performance of concrete made with fine recycled concrete aggregates. *Cement & Concrete Composites*, 34, 1044-1052.

[113] Pereira-De-Oliveira, L. A., Nepomuceno, M. C. S., Castro-Gomes, J. P., & Vila, M. F. C. (2014). Permeability properties of self-compacting concrete with coarse recycled aggregates. *Construction and Building Materials,* 51, 113-120.

[114] Poon, C. S., Kou, S. C., & Lam, L. (2007). Influence of recycled aggregate on slump and bleeding of fresh concrete. *Materials and Structures*, 40(9), 981-988.

[115] Poon, C. S., & Chan, D. (2006). Feasible use of recycled concrete aggregates and crushed clay brick as unbound road sub-base. *Construction and Building Materials*, 20(8), 578-585.

[116] Poon, C. S., & Chan, D. (2006). Paving blocks made with recycled concrete aggregate and crushed clay brick. *Construction and Building Materials*, 20(8), 569-577.

[117] Poon, C. S., Shui, Z. H., & Lam, L. (2004). Effect of microstructure of ITZ on compressive strength of concrete prepared with recycled aggregates. *Construction and Building Materials*, 18(6), 461-468.

[118] Poon, C. S., Shui, Z. H., Lam, L., Fok, H., & Kou, S. C. (2004). Influence of moisture states of natural and recycled aggregates on the slump and compressive strength of concrete. *Cement and Concrete Research*, 34(1), 31-36.

[119] Qasrawi, H., & Marie, I. (2013). Towards better understanding of concrete containing recycled concrete aggregate. *Advances in Materials Science and Engineering,* 2013, article ID 636034, 8 pp.

[120] Rahal, K. (2007). Mechanical properties of concrete with recycled coarse aggregate. *Building and Environment,* 42(1), 407-415.

[121] Randonjanin, V., Malešev, M., & Marinkovi, S. (2012). Recycled concrete as aggregate for structural concrete production. *The Masterbuilder*, May 2012, 58-72.

[122] Ravindrarajah Sri, R., Loo, Y. H., & Tam, C. T. (1987). Recycled concrete as fine and coarse aggregates in concrete. *Magazine of Concrete Research*, 39(141), 214-220.

[123] Ravindrarajah Sri, R., & Tam, C. T. (1985). Properties of concrete made with crushed concrete as coarse aggregate. *Magazine of Concrete Research*, 37(130), 29-38.

[124] Safiuddin, M., Alengaram, U. J., Salam, M. A., Jumaat, M. Z., Jaafar, F. F., & Saad, H. B. (2011). Properties of high-workability concrete with recycled concrete aggregate. *Materials Research*, 14(2), 248-255.

[125] Salem, R. M., Burdette, E. G., & Jackson, N. M. (2003). Resistance to freezing and thawing of recycled aggregate concrete. *ACI Materials Journal*, 100(3), 216-221.

[126] Saravana Kumar, P., & Dhinakaran, G. (2012). Effect of admixed recycled aggregate concrete on properties of fresh and hardened concrete. *Journal of Materials in Civil Engineering,* 24(4), 494-498.

[127] Sato, R., Maruyama, I., Sogabe, T., & Sogo, M. (2007). Flexural behavior of reinforced recycled concrete beams. *Journal of Advanced Concrete Technology*, 5(1), 43-61.

[128] Seara-Paz, S., González-Fonteboa, B., Eiras-López, J., & Herrador, M. F. (2014). Bond behavior between steel reinforcement and recycled concrete. *Materials and Structures,* 47(1-2), 323-334.

[129] Seung-Tae, L. (2009). Influence of recycled fine aggregates on the resistance of mortars to magnesium sulfate attack. *Waste Management*, 29(8), 2385-2391.

[130] Soares, D., de Brito, J., Ferreira, J., & Pacheco, J. (2014). Use of coarse recycled aggregates from precast concrete rejects: mechanical and durability performance. *Construction and Building Materials*, 71, 263-272.

[131] Somna, R., Jaturapitakkul, C., Chalee, W., & Rattanachu, P. (2012). Effect of the water to binder ratio and ground fly ash on properties of recycled aggregate concrete. *Journal of Materials in Civil Engineering,* 24(1), 16-22.

[132] Sun, Y., & Xiang, X. (2011). Experiment research on basic mechanic property of recycled concrete with different ratio of recycled aggregate. *Advanced Materials Research*, vols. 250-253, pp. 994-1000.

[133] Takayuki, F., & Masaru, Y. (2003). Strength and drying shrinkage of concrete used recycled aggregate. Mem. Fac. Eng., Osaka City Univ., 44, 79-82.

[134] Tam, V. W. Y., Gao, X. F., Tam, C. M., & Ng, K. M. (2009). Physio-chemical reactions in recycle aggregate concrete. *Journal of Hazardous Materials*, 163(2-3), 823-828.

[135] Tam, V. W. Y., & Le, K. N. (2007). Optimal aggregate testing using vandermonde polynomials and spectral methods. *Journal of Hazardous Materials*, 145(1-2), 72-99.

[136] Tangchirapat, W., Buranasing, R., & Jaturapitakkul, C. (2010). Use of high fineness of fly ash to improve properties of recycled aggregate concrete. *Journal of Materials in Civil Engineering*, 22(6), 565-571.

[137] Thomas, C., Sosa, I., Setién, J., Polanco, J. A., & Cimentada, A. I. (2014). Evaluation of the fatigue behavior of recycled aggregate concrete. *Journal of Cleaner Production*, 65, 397-405.

[138] Thomas, C., Setién, J., Polanco, J. A., Alaejos, P., & Sánchez de Juan, M. (2013). Durability of recycled aggregate concrete. *Construction and Building Materials*, 40, 1054-1065.

[139] Tuyan, M., Mardani-Aghabaglou, A., & Ramyar, K. (2014). Freeze-thaw resistance, mechanical and transport properties of self-consolidating concrete incorporating coarse recycled concrete aggregate. *Materials and Design,* 53, 983-991.

[140] Vieira, J. P. B., Correia, J. R., & De Brito, J. (2011). Post-fire residual mechanical properties of concrete made with recycled concrete coarse aggregates. *Cement and Concrete Research*, 41(5), 533-541.

[141] Villagrán-Zaccardi, Y. A., Zega, C. J., & Di Maio, Á. A. (2008). Chloride penetration and binding in recycled concrete. *Journal of Materials in Civil Engineering*, 20(6), 449-455.

[142] Wang, W., Kou, S., & Xing, F. (2013). Deformation properties and direct shear of medium strength concrete prepared with 100% recycled coarse aggregates. *Construction and Building Materials,* 48, 187-193.

[143] Won, L., Sang, J., & Hyun, D. (2008). Shear strength of reinforced concrete beams with recycled aggregates. In Tailor Made Concrete Structures (pp. 225-225) CRC Press.

[144] Xiao, J., Huang, X., & Shen, L. (2012). Seismic behavior of semi-precast column with recycled aggregate concrete. *Construction and Building Materials,* 35, 988-1001.

[145] Xiao, J., Xie, H., & Yang, Z. (2012). Shear transfer across a crack in recycled aggregate concrete. *Cement and Concrete Research,* 42(5), 700-709.

[146] Xuping, L. (2009). Recycling and reuse of waste concrete in china: Part II. Structural behaviour of recycled aggregate concrete and engineering applications. *Resources, Conservation and Recycling*, 53(3), 107-112.

[147] Yildirim, S. T., Meyer, C., & Herfellner, S. (2015). Effects of internal curing on the strength, drying shrinkage and freeze-thaw resistance of concrete containing recycled concrete aggregates. *Construction and Building Materials,* 91, 288-296.

[148] Younis, K. H., & Pilakoutas, K. (2013). Strength prediction model and methods for improving recycled aggregate concrete. *Construction and Building Materials,* 49, 688-701.

[149] Zaharieva, R., Buyle-Bodin, F., Skoczylas, F., & Wirquin, E. (2003). Assessment of the surface permeation properties of recycled aggregate concrete. *Cement and Concrete Composites*, 25(2), 223-232.

[150] Zega, C. J., & Di Maio, Á. A. (2011). Use of recycled fine aggregate in concretes with durable requirements. *Waste Management*, 31(11), 2336-2340.

[151] Zhang, W., & Ingham, J. M. (2010). Using recycled concrete aggregates in New Zealand ready-mix concrete production. *Journal of Materials in Civil Engineering*, 22(5), 443-450.

[152] Zhao, X., & Duan, M. (2013). Experimental research on mechanical properties of recycled aggregate concrete under uniaxial loading. *Advanced Materials Research*, 671-674, 1736-1740.

REFERENCES – RECYCLED CONCRETE DATABASE

[1] Corinaldesi, V. (2010). Mechanical and elastic behaviour of concretes made of recycled-concrete coarse aggregates. *Construction and Building Materials*, 24(9), 1616-1620.

[2] Pelufo, M. J., Domingo, A., Ulloa, V. A., & Vergara, N. N. (2009). Analysis of moisture state of recycled coarse aggregate and its influence on compression strength of the concrete. Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2009, Valencia.

[3] Poon, C. S., Shui, Z. H., Lam, L., Fok, H., & Kou, S. C. (2004). Influence of moisture states of natural and recycled aggregates on the slump and compressive strength of concrete. *Cement and Concrete Research*, 34(1), 31-36.

[4] De Oliveira, M. B., & Vazquez, E. (1996). The influence of retained moisture in aggregates from recycling on the properties of new hardened concrete. *Waste Management*, 16(1-3), 113-117.

[5] Casuccio, M., Torrijos, M. C., Giaccio, G., & Zerbino, R. (2008). Failure mechanism of recycled aggregate concrete. *Construction and Building Materials*, 22(7), 1500-1506.

[6] Etxeberria, M., Vázquez, E., Marí, A., & Barra, M. (2007). Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete. *Cement and Concrete Research*, 37(5), 735-742.

[7] Rahal, K. (2007). Mechanical properties of concrete with recycled coarse aggregate. *Building and Environment,* 42(1), 407-415.

[8] González-Fonteboa, B., Martínez-Abella, F., Carro-López, D., & Seara-Paz, S. (2011). Stress-strain relationship in axial compression for concrete using recycled saturated coarse aggregate. *Construction and Building Materials*, 25(5), 2335-2342.

[9] Berndt, M. L. (2009). Properties of sustainable concrete containing fly ash, slag and recycled concrete aggregate. *Construction and Building Materials*, 23(7), 2606-2613.

[10] Angulo, S. C., Carrijo, P. M., Figueiredo, A. D., Chaves, A. P., & John, V. M. (2010). On the classification of mixed construction and demolition waste aggregate by porosity and its impact on the mechanical performance of concrete. *Materials and Structures*, 43(4), 519-528.

[11] Corinaldesi, V., Letelier, V., & Moriconi, G. (2011). Behaviour of beam-column joints made of recycled-aggregate concrete under cyclic loading. *Construction and Building Materials*, 25(4), 1877-1882.

[12] Gómez-Soberón, J. M. V. (2002). Porosity of recycled concrete with substitution of recycled concrete aggregate: An experimental study. *Cement and Concrete Research*, 32(8), 1301-1311.

[13] Barra, M., & Vázquez, E. (1997). Particularidades do proceso de carbonatação em concretos de agregado reciclado. IV Congreso Iberoamericano de Patología de las Construcciones, VI Congreso de Control y Calidad, Octubre 1997, Brasil.

[14] Etxeberria, M., Marí, A. R., & Vázquez, E. (2007). Recycled aggregate concrete as structural material. *Materials and Structures*, 40(5), 529-541.

[15] Evangelista, L., & de Brito, J. (2007). Mechanical behaviour of concrete made with fine recycled concrete aggregates. *Cement and Concrete Composites*, 29(5), 397-401.

[16] Debieb, F., Courard, L., Kenai, S., & Degeimbre, R. (2009). Roller compacted concrete with contaminated recycled aggregates. *Construction and Building Materials*, 23(11), 3382-3387.

[17] Debieb, F., Courard, L., Kenai, S., & Degeimbre, R. (2010). Mechanical and durability properties of concrete using contaminated recycled aggregates. *Cement and Concrete Composites*, 32(6), 421-426.

[18] Villagrán-Zaccardi, Y. A., Zega, C. J., & Di Maio, Á. A. (2008). Chloride penetration and binding in recycled concrete. *Journal of Materials in Civil Engineering*, 20(6), 449-455.

[19] Ortega, N. F., Moro, J.M., Meneses, R., & Aveldaño, R. R. (2010). Comportamiento dinámico de vigas de hormigón reciclado con sus armaduras corroídas. VI Congreso Internacional sobre Patología y Recuperación de Estructuras, June 2010, Argentina.

[20] Di Maio, A. A., & Traversa, L. P. (2003). Evaluation of recycled concrete by means of non destructive tests [Evaluación de hormigones reciclados mediante ensayos no destructivos]. *Materiales De Construcción*, 53(271-272), 37-46.

[21] De Juan, M. S. (2004). Estudio sobre la utilización de árido reciclado para la fabricación de Hormigón Estructural. PhD Dissertation, Polytechnic University of Madrid, Spain.

[22] Ferreira, L., De Brito, J., & Barra, M. (2011). Influence of the pre-saturation of recycled coarse concrete aggregates on concrete properties. *Magazine of Concrete Research*, 63(8), 617-627.

[23] Corinaldesi, V. (2011). Structural concrete prepared with coarse recycled concrete aggregate: From investigation to design. *Advances in Civil Engineering*, 2011.

[24] Poon, C. S., Kou, S. C., & Lam, L. (2007). Influence of recycled aggregate on slump and bleeding of fresh concrete. *Materials and Structures*, 40(9), 981-988.

[25] Chakradhara Rao, M., Bhattacharyya, S. K., & Barai, S. V. (2011). Influence of field recycled coarse aggregate on properties of concrete. *Materials and Structures*, 44(1), 205-220.

[26] Ravindrarajah Sri, R., Loo, Y. H., & Tam, C. T. (1987). Recycled concrete as fine and coarse aggregates in concrete. *Magazine of Concrete Research*, 39(141), 214-220.

[27] Ajdukiewicz, A., & Kliszczewicz, A. (2002). Influence of recycled aggregates on mechanical properties of HS/HPC. *Cement and Concrete Composites*, 24(2), 269-279.

[28] Corinaldesi, V., & Moriconi, G. (2010). Recycling of rubble from building demolition for low-shrinkage concretes. *Waste Management*, 30(4), 655-659.

[29] Buyle-Bodin, F., & Hadjieva-Zaharieva, R. (2002). Influence of industrially produced recycled aggregates on flow properties of concrete. *Materials and Structures*, 35(252 SPEC.), 504-509.

[30] Domingo-Cabo, A., Lázaro, C., López-Gayarre, F., Serrano-López, M. A., Serna, P., & Castaño-Tabares, J. O. (2009). Creep and shrinkage of recycled aggregate concrete. *Construction and Building Materials*, 23(7), 2545-2553.

[31] Khatib, J. M. (2005). Properties of concrete incorporating fine recycled aggregate. *Cement and Concrete Research*, 35(4), 763-769.

[32] Tangchirapat, W., Buranasing, R., & Jaturapitakkul, C. (2010). Use of high fineness of fly ash to improve properties of recycled aggregate concrete. *Journal of Materials in Civil Engineering*, 22(6), 565-571.

[33] Malešev, M., Radonjanin, V., & Marinković, S. (2010). Recycled concrete as aggregate for structural concrete production. *Sustainability*, 2(5), 1204-1225.

[34] Kou, S., Poon, C., & Etxeberria, M. (2011). Influence of recycled aggregates on long term mechanical properties and pore size distribution of concrete. *Cement and Concrete Composites*, 33(2), 286-291.

[35] Kou, S., & Poon, C. (2010). Properties of concrete prepared with PVA-impregnated recycled concrete aggregates. *Cement and Concrete Composites*, 32(8), 649-654.

[36] Kou, S., & Poon, C. (2009). Properties of concrete prepared with crushed fine stone, furnace bottom ash and fine recycled aggregate as fine aggregates. *Construction and Building Materials*, 23(8), 2877-2886.

[37] Bhikshma, V., & Kishore, R. (2010). Development of stress - strain curves for recycled aggregate concrete. *Asian Journal of Civil Engineering*, 11(2), 253-261.

[38] Vieira, J. P. B., Correia, J. R., & De Brito, J. (2011). Post-fire residual mechanical properties of concrete made with recycled concrete coarse aggregates. *Cement and Concrete Research*, 41(5), 533-541.

[39] Sun, Y., & Xiang, X. (2011). Experiment research on basic mechanic property of recycled concrete with different ratio of recycled aggregate. *Advanced Materials Research*, vols. 250-253, 994-1000.

[40] Li, Y., Tao, J., Lei, T., & Xie, J. (2011). Experimental study on compressive strength of recycled concrete. *Advanced Materials Research*, 261-263, 75-78.

[41] Safiuddin, M., Alengaram, U. J., Salam, M. A., Jumaat, M. Z., Jaafar, F. F., & Saad, H. B. (2011). Properties of high-workability concrete with recycled concrete aggregate. *Materials Research*, 14(2), 248-255.

[42] Chakradhara Rao, M., Bhattacharyya, S. K., & Barai, S. V. (2011). Behaviour of recycled aggregate concrete under drop weight impact load. *Construction and Building Materials*, 25(1), 69-80.

[43] Batayneh, M., Marie, I., & Asi, I. (2007). Use of selected waste materials in concrete mixes. *Waste Management*, 27(12), 1870-1876.

[44] Castaño, J. O., Domingo, A., & Lázaro, C. (2009). A study on drying shrinkage and creep of recycled concrete aggregate. Proceedings of the International Association for Shell and Spatial Structures (IASS) Symposium 2009, Valencia.

[45] Chen, Z., Huang, K., Zhang, X., & Xue, J. (2010). Experimental research on the flexural strength of recycled coarse aggregate concrete. In: 2010 International Conference on Mechanic Automation and Control Engineering, 26-28 June 2010, Wuhan, China, 1041-1043.

[46] Ann, K. Y., Moon, H. Y., Kim, Y. B., & Ryou, J. (2008). Durability of recycled aggregate concrete using pozzolanic materials. *Waste Management*, 28(6), 993-999.

[47] Corinaldesi, V., & Moriconi, G. (2009). Influence of mineral additions on the performance of 100% recycled aggregate concrete. *Construction and Building Materials*, 23(8), 2869-2876.

[48] Courard, L., Michel, F., & Delhez, P. (2010). Use of concrete road recycled aggregates for roller compacted concrete. *Construction and Building Materials*, 24(3), 390-395.

[49] Zaharieva, R., Buyle-Bodin, F., Skoczylas, F., & Wirquin, E. (2003). Assessment of the surface permeation properties of recycled aggregate concrete. *Cement and Concrete Composites*, 25(2), 223-232.

[50] Katz, A. (2004). Treatments for the improvement of recycled aggregate. *Journal of Materials in Civil Engineering*, 16(6), 597-603.

[51] Kou, S. C., Poon, C. S., & Dixon, C. (2007). Influence of fly ash as cement replacement on the properties of recycled aggregate concrete. *Journal of Materials in Civil Engineering*, 19(9), 709-717.

[52] Otsuki, N., Miyazato, S., & Yodsudjai, W. (2003). Influence of recycled aggregate on interfacial transition zone, strength, chloride penetration and carbonation of concrete. *Journal of Materials in Civil Engineering*, 15(5), 443-451.

[53] Nagataki, S., Gokce, A., Saeki, T., & Hisada, M. (2004). Assessment of recycling process induced damage sensitivity of recycled concrete aggregates. *Cement and Concrete Research*, 34(6), 965-971.

[54] Poon, C. S., Shui, Z. H., & Lam, L. (2004). Effect of microstructure of ITZ on compressive strength of concrete prepared with recycled aggregates. *Construction and Building Materials*, 18(6), 461-468.

[55] Lin, Y., Tyan, Y., Chang, T., & Chang, C. (2004). An assessment of optimal mixture for concrete made with recycled concrete aggregates. *Cement and Concrete Research*, 34(8), 1373-1380.

[56] Kou, S. C., Poon, C. S., & Chan, D. (2008). Influence of fly ash as a cement addition on the hardened properties of recycled aggregate concrete. *Materials and Structures*, 41(7), 1191-1201.

[57] Zega, C. J., & Di Maio, Á. A. (2011). Use of recycled fine aggregate in concretes with durable requirements. *Waste Management*, 31(11), 2336-2340.

[58] Chen, A., Wang, J., & Ge, Z. (2011). Experimental study on the fundamental characteristics of recycled concrete. *Advanced Materials Research*, 295-297, 958-961.

[59] Salem, R. M., Burdette, E. G., & Jackson, N. M. (2003). Resistance to freezing and thawing of recycled aggregate concrete. *ACI Materials Journal*, 100(3), 216-221.

[60] Garg, A., Koster, G., & Rühl, M. (1998). Implementation of long term measurements at a building made of concrete with aggregate derived from concrete rubble. http://www.b-i-m.de/public/tudmassiv/dacon13gargkoster.htm

[61] Grübl, P., & Nealen, A. (1998). Construction of an office building using concrete made from recycled demolition material. *Aus Darmstadt Concrete*, 13.

[62] Kalaiarasu, S. M., & Subramanian, K. (2006). Properties of recycled aggregate concrete with silica fume. *Journal of Applied Sciences*, 6(14), 2956-2958.

[63] Won, L., Sang, J., & Hyun, D. (2008). Shear strength of reinforced concrete beams with recycled aggregates. In Tailor Made Concrete Structures (pp. 225-225) CRC Press.

[64] Li, J., Xiao, H., & Zhou, Y. (2009). Influence of coating recycled aggregate surface with pozzolanic powder on properties of recycled aggregate concrete. *Construction and Building Materials*, 23(3), 1287-1291.

[65] Kong, D., Lei, T., Zheng, J., Ma, C., Jiang, J., & Jiang, J. (2010). Effect and mechanism of surface-coating pozzolanics materials around aggregate on properties and ITZ microstructure of recycled aggregate concrete. *Construction and Building Materials*, 24(5), 701-708.

[66] Peng, G. F., Liu, Q. B., Guo, Z. B., Hou, Q. X., Cao, S. Q., & Zhang, J. F. (2011). Mechanical properties and permeability of recycled aggregate concrete at low water/binder ratio.

[67] Sato, R., Maruyama, I., Sogabe, T., & Sogo, M. (2007). Flexural behavior of reinforced recycled concrete beams. *Journal of Advanced Concrete Technology*, 5(1), 43-61.

[68] Manzi, S., Mazzotti, C., & Bignozzi, M. C. (2013). Short and long-term behavior of structural concrete with recycled concrete aggregate. *Cement and Concrete Composites,* 37(1), 312-318.

[69] Mefteh, H., Kebaïli, O., Oucief, H., Berredjem, L., & Arabi, N. (2013). Influence of moisture conditioning of recycled aggregates on the properties of fresh and hardened concrete. *Journal of Cleaner Production,* 54, 282-288.

[70] Kim, K., Shin, M., & Cha, S. (2013). Combined effects of recycled aggregate and fly ash towards concrete sustainability. *Construction and Building Materials,* 48, 499-507.

[71] Cui, H. Z., Shi, X., Memon, S. A., Xing, F., & Tang, W. (2014). Experimental study on the influence of water absorption of recycled coarse aggregates on properties of the resulting concretes. *Journal of Materials in Civil Engineering,* 27(4)

[72] González-Fonteboa, B., Martínez-Abella, F., Herrador, M. F., & Seara-Paz, S. (2012). Structural recycled concrete: Behaviour under low loading rate. *Construction and Building Materials,* 28(1), 111-116.

[73] Seara-Paz, S., González-Fonteboa, B., Eiras-López, J., & Herrador, M. F. (2014). Bond behavior between steel reinforcement and recycled concrete. *Materials and Structures,* 47(1-2), 323-334.

[74] Folino, P., & Xargay, H. (2014). Recycled aggregate concrete - mechanical behavior under uniaxial and triaxial compression. *Construction and Building Materials,* 56, 21-31.

[75] Gomes, M., de Brito, J., & Bravo, M. (2014). Mechanical performance of structural concrete with the incorporation of coarse recycled concrete and ceramic aggregates. *Journal of Materials in Civil Engineering,* 26(10).

[76] González, A., & Etxeberria, M. (2014). Experimental analysis of properties of high performance recycled aggregate concrete. *Construction and Building Materials,* 52, 227-235.

[77] Pedro, D., De Brito, J., & Evangelista, L. (2014). Influence of the use of recycled concrete aggregates from different sources on structural concrete. *Construction and Building Materials,* 71, 141-151.

[78] Pepe, M., Toledo Filho, R. D., Koenders, E. A. B., & Martinelli, E. (2014). Alternative processing procedures for recycled aggregates in structural concrete. *Construction and Building Materials,* 69, 124-132.

[79] Barbudo, A., De Brito, J., Evangelista, L., Bravo, M., & Agrela, F. (2013). Influence of water-reducing admixtures on the mechanical performance of recycled concrete. *Journal of Cleaner Production,* 59, 93-98.

[80] Kou, S., & Poon, C. (2013). Long-term mechanical and durability properties of recycled aggregate concrete prepared with the incorporation of fly ash. *Cement and Concrete Composites,* 37(1), 12-19.

[81] Kou, S., & Poon, C. (2015). Effect of the quality of parent concrete on the properties of high performance recycled aggregate concrete. *Construction and Building Materials,* 77, 501-508.

APPENDIX A
Extended summary in Spanish

Hormigón autocompactante reciclado: propiedades mecánicas básicas, reología, robustez y tixotropía

Este trabajo se centra en el estudio del comportamiento en estado fresco y endurecido del hormigón autocompactante reciclado (HACR). El objetivo principal es aplicar los principios de la reología al HACR para entender en profundidad su comportamiento en estado fresco y analizar también sus propiedades mecánicas básicas.

En este trabajo, el árido reciclado utilizado es árido grueso reciclado de hormigón, diseñándose diferentes mezclas de HACR en las que se sustituye en volumen el árido grueso natural por el reciclado.

De acuerdo a la bibliografía, es de esperar que el hormigón autocompactante (HAC) presente propiedades en estado endurecido similares a las de su hormigón vibrado equivalente. Por lo tanto, el primer objetivo general de este trabajo es demostrar que es posible predecir las propiedades del HACR (resistencia a compresión, módulo de elasticidad y resistencia a tracción) utilizando expresiones ajustadas con hormigones vibrados reciclados.

Por otro lado, en estado fresco, es de esperar que el HACR muestre una mayor influencia de las singularidades del hormigón reciclado y del hormigón autocompactante (las propiedades particulares del árido reciclado y un comportamiento especial en estado fresco, respectivamente). Por lo tanto, este trabajo pretende también analizar la especificidad del diseño de un HACR con características de trabajabilidad (capacidad de flujo, capacidad de paso y resistencia a la segregación), reología y robustez adecuadas, y estudiar su comportamiento tixotrópico.

En este sentido, el segundo de los objetivos generales es determinar el efecto de la incorporación de árido grueso reciclado de hormigón en las propiedades en estado fresco del hormigón autocompactante. El estudio se centra en su comportamiento reológico (incluyendo las tres características de trabajabilidad y la evolución temporal tanto de estas como de su reología), en su robustez y en el análisis de su tixotropía (evaluando, además, su influencia en la adherencia entre capas).

Para la consecución de estos objetivos se desarrolla una extensa campaña experimental que se divide en tres fases. En la primera de ellas, llamada "Reología", se estudian cuatro tipos de hormigón autocompactante, un hormigón de referencia y tres hormigones reciclados. Los porcentajes de sustitución de árido grueso natural por árido grueso reciclado de hormigón son 0%, 20%, 50% y 100% (en volumen). En esta primera fase se utilizan, para cada mezcla, tres métodos de amasado:

1. Método M1: los áridos se utilizan en condiciones secas y se añade una cantidad de agua extra durante el amasado. Esta se calcula para compensar la absorción del árido reciclado a los 10 min (80% de la absorción a las 24 h).

2. Método M2: el árido reciclado se presatura hasta el 80% de su capacidad de absorción de agua total inmediatamente antes del amasado.
3. Método M3: el árido reciclado se utiliza con un 3% de humedad natural y de nuevo se añade una cantidad de agua extra durante el amasado de acuerdo al mismo criterio que en el método M1.

En la segunda fase, denominada “Robustez”, se realiza una campaña experimental para evaluar la robustez del hormigón autocompactante conteniendo árido reciclado. Se estudian dos series de mezclas de hormigón autocompactante con diferentes porcentajes de árido grueso reciclado de hormigón (0%, 20%, 50% y 100%), una serie con el árido en condiciones secas (método M1) y la otra incorporándolo en la amasadora con un 3% de humedad (método M3). En esta segunda fase, se analiza la capacidad del HACR para mantener su trabajabilidad y sus propiedades reológicas a lo largo del tiempo cuando se introducen variaciones en el agua (± 3%), en el superplastificante (± 5%) y en el cemento (± 3%) de forma independiente.

En ambas fases de trabajo, “Reología” y “Robustez”, se miden las propiedades en estado fresco del HACR mediante reómetro (tensión de flujo umbral y viscosidad plástica) y mediante ensayos empíricos (escurrimiento, caja en L, embudo en V, anillo japonés y segregación por tamiz). Tanto los ensayos empíricos como reológicos se realizan sobre todas las mezclas a 15, 45 y 90 min desde el contacto entre cemento y agua.

Para analizar el comportamiento en estado endurecido del HACR, en ambas fases, se determinó para cada mezcla la densidad en fresco y en endurecido y la resistencia a compresión a 3, 7 y 28 días.

La tercera fase, llamada “Tixotropía”, se centra en el análisis del comportamiento tixotrópico del HACR. Además, se evalúan la adherencia y permeabilidad al agua que pueden desarrollarse entre tongadas sucesivas de hormigón autocompactante reciclado tras un cierto período de reposo. Para este propósito, se estudian cuatro mezclas de HACR con 0%, 20%, 50% y 100% de árido grueso reciclado. Este árido se utiliza seco y se añade una cantidad extra de agua durante el amasado para compensar su absorción a los 10 min (método M1).

En esta tercera fase, en relación con el comportamiento en estado endurecido, se miden la resistencia a compresión, resistencia a tracción y módulo de elasticidad a 28 días para cada mezcla.

En relación con el comportamiento en estado endurecido, se ha creado una base de datos con resultados publicados sobre hormigón vibrado reciclado y se han ajustado diferentes coeficientes de corrección para adaptar las expresiones normativas a este tipo de hormigón. Asimismo, se han ajustado expresiones predictivas específicas para el hormigón vibrado reciclado como alternativa a las formulaciones de las normativas. Finalmente, se ha confirmado que, tanto los coeficientes de corrección como las expresiones específicas, pueden utilizarse en el HACR con la misma precisión que en el hormigón vibrado reciclado. Por lo tanto, la incorporación de árido grueso reciclado de hormigón afecta a la resistencia a compresión, módulo de elasticidad y resistencia a tracción del hormigón autocompactante en la misma medida en que se afectan en el hormigón vibrado.

En relación con el comportamiento en estado fresco, se puede concluir que las mismas relaciones entre parámetros empíricos y entre parámetros empíricos y propiedades reológicas se pueden utilizar para hormigones autocompactantes convencionales y reciclados. Además, de acuerdo a los resultados obtenidos y en consonancia con otros autores, ninguno de los ensayos empíricos se encuentra adecuado para definir todas las características clave de la trabajabilidad del HACR como un único ensayo, y no hay ninguna combinación de ensayos que haya logrado una validez universal.

El análisis del comportamiento reológico muestra que la particularidad del HACR radica en la cantidad de agua extra necesaria para compensar la absorción del árido grueso reciclado durante el protocolo de amasado, que influye en la relación agua/cemento efectiva ($(a/c)_{ef}$), y en las características intrínsecas del mismo (forma, textura y contenido de finos). En este trabajo, dado que árido reciclado y natural presentan formas similares (ambos son de machaqueo), son principalmente la textura rugosa y el contenido de finos en el árido reciclado y generados durante el amasado por el desgaste del mortero adherido, los que modifican el comportamiento reológico del HACR. Todas estas singularidades llevan a diferentes relaciones o curvas “variaciones reológicas – $(a/c)_{ef}$” y “variaciones reológicas – $Ø/Ø_{max}$” en un HACR comparado con un hormigón autocompactante convencional.

Las diferencias obtenidas entre el comportamiento de un hormigón autocompactante convencional y el de un HACR con el transcurso del tiempo dependen de la cantidad de agua compensada en el protocolo de amasado. Esta determina la región de las curvas “variaciones reológicas – $(a/c)_{ef}$” donde el hormigón se ha diseñado. Está claro que la relación agua/cemento efectiva del HACR evoluciona con el tiempo de acuerdo a la evolución de la absorción del árido grueso reciclado. Entonces, es más probable que la región con pendiente pronunciada de las curvas mencionadas se alcance cuando se utilicen altos porcentajes de árido reciclado, cuando se diseñe el HACR con una relación agua/cemento baja y/o cuando se mida el comportamiento a largo plazo del HACR. En estos casos, es de esperar un comportamiento reológico dependiente del tiempo en un HACR diferente de un HAC, de lo contrario el comportamiento reológico a lo largo del tiempo del HACR será similar al de un HAC.

El análisis de la robustez del HACR se realiza a través del cálculo de parámetros de sensibilidad para definir los factores que afectan a esta propiedad en mayor medida. También se efectúa una aproximación estadística para determinar qué ensayos proporcionan mayor sensibilidad cuando se evalúa la robustez del HACR.

Ambos análisis muestran que el principal parámetro que afecta a la robustez del HACR es el agua. Por otro lado, dado que el control del agua resulta más difícil en este hormigón, debido a la mayor absorción del árido reciclado, este debe ser más exhaustivo que en el HAC convencional. Además, la aproximación estadística, basada en el coeficiente de concordancia de Kendall y el coeficiente de correlación de Spearman, se utilizó satisfactoriamente para identificar las propiedades clave a medir para evaluar la robustez del HACR: tensión de flujo umbral estática (15 min), viscosidad plástica (15 min), tiempo y diámetro del ensayo de escurrimiento (15 min), diámetro del ensayo con el anillo japonés (15 min) y la resistencia a la segregación por tamiz.

Finalmente, se observa que el HACR es menos robusto que el hormigón autocompactante convencional. Esto se debe a que el HACR presenta las curvas “parámetro reológico – $(a/c)_{ef}$” y “parámetro reológico - $Ø/Ø_{max}$” con mayor pendiente que las del hormigón autocompactante convencional. De esta forma, cuando se utilizan altos porcentajes de árido grueso reciclado existe una mayor probabilidad de alcanzar la región de pendiente pronunciada de estas curvas de mayor pendiente. Esto causa cambios significativos en la tensión de flujo umbral estática y, de forma similar, cambios sustanciales en la viscosidad plástica y en los parámetros empíricos. Adicionalmente, la fabricación de los hormigones con áridos con contenido de humedad dificulta más el diseño de HACRs robustos, como también ocurre en los hormigones autocompactantes convencionales.

Por lo tanto, en conclusión, la robustez del HACR dependerá de la cantidad de agua compensada en el protocolo de amasado y en la región de la curva “parámetro reológico – $(a/c)_{ef}$”, donde el hormigón ha sido diseñado (cerca o lejos de la zona de pendiente pronunciada).

El estudio del grado de tixotropía del HACR se aborda utilizando varios métodos de ensayo y protocolos: curvas de ruptura estructural a diferentes velocidades de rotación, curvas de flujo de histéresis y tensión de flujo en reposo (también llamada tensión de flujo estática). Adicionalmente, se evalúa la influencia de la tixotropía o el efecto de la reestructuración en reposo en el comportamiento mecánico del HACR a través de la medida de la adherencia entre capas utilizando ensayos a flexión y ensayos de permeabilidad al agua. Los tiempos entre dos tongadas sucesivas de HACR son de 0, 15, 30 y 60 min.

De acuerdo a los resultados obtenidos, se puede concluir que los tres métodos utilizados proporcionan, aunque midiendo diferentes índices, resultados similares sobre el grado de tixotropía de cada mezcla, esto quiere decir que con los tres métodos se obtienen las mismas conclusiones cualitativas. Adicionalmente, se observa que los ensayos de curvas de ruptura estructural y de tensión de flujo en reposo proporcionan mayor sensibilidad en la aproximación al comportamiento tixotrópico.

Como la tixotropía depende de la composición de la pasta y esta es similar en todos los hormigones, las diferencias observadas en los índices de tixotropía de las diferentes mezclas son pequeñas, constatándose un ligero incremento cuando el porcentaje de sustitución es total. Este incremento se debe a la diferencia en la relación agua/cemento efectiva, resultado de la absorción no compensada, y a la mayor cantidad de finos generados por el viejo mortero adherido al árido grueso reciclado.

La relación agua/cemento efectiva diseñada en esta fase sitúa a los hormigones en la región de pendiente suave de sus curvas “variaciones reológicas – $(a/c)_{ef}$”. De esta forma, su evolución temporal hasta el tiempo considerado en esta fase de trabajo (debida a la absorción no compensada), no implica cambios significativos en la composición de las pastas de los HACRs. Por lo tanto, la velocidad de reestructuración es similar en todas las mezclas estudiadas.

Los resultados de resistencia a flexión residual y variación de la profundidad de penetración de agua indican, para todos los tiempos entre capas considerados, que los HACRs desarrollan una adherencia entre capas similar a la del hormigón autocompactante de referencia. Solamente para un tiempo entre capas de 60 min, se ha observado que, para el porcentaje de sustitución total, el decremento en la adherencia es ligeramente más notable. Esto se debe a que la tixotropía de los HACRs estudiados es ligeramente mayor cuando se utilizan altos porcentajes de sustitución

Finalmente, en consonancia con las conclusiones del análisis de la reología, cuando se utilizan altos porcentajes de sustitución, cuando el HACR se diseña con una relación agua/cemento baja (en la región de pendiente pronunciada de las curvas “variaciones reológicas – $(a/c)_{ef}$”) y/o cuando se mide el comportamiento autocompactante a largo plazo, la velocidad de reestructuración y la adherencia entre capas pueden verse más afectadas en los HACRs que en el hormigón autocompactante convencional.

APPENDIX B
Extended summary in Galician

Formigón autocompactante reciclado: propiedades mecánicas básicas, reoloxía, robustez e tixotropía

Este traballo céntrase no estudo do comportamento no estado fresco e endurecido do formigón autocompactante reciclado (FACR). O obxectivo principal é aplicar os principios da reoloxía ao FACR para entender en profundidade o seu comportamento no estado fresco e analizar tamén as súas propiedades mecánicas básicas.

Neste traballo, o árido reciclado utilizado é árido groso reciclado de formigón, deseñándose diferentes mesturas de FACR nas que se substitúe en volume o árido groso natural polo reciclado.

Conforme á bibliografía, é de esperar que o formigón autocompactante (FAC) presente propiedades no estado endurecido similares ás do seu formigón vibrado equivalente. Polo tanto, o primeiro obxectivo xeral deste traballo é demostrar que é posible predicir as propiedades do FACR (resistencia a compresión, módulo de elasticidade e resistencia a tracción) utilizando expresións axustadas con formigóns vibrados reciclados.

Por outro lado, no estado fresco, é de esperar que o FACR mostre unha maior influencia das singularidades do formigón reciclado e do formigón autocompactante (as propiedades particulares do árido reciclado e un comportamento especial no estado fresco, respectivamente). Polo tanto, este traballo pretende tamén analizar a especificidade do deseño dun FACR con características de traballabilidade (capacidade de fluxo, capacidade de paso e resistencia á segregación), reoloxía e robustez adecuadas, e estudar o seu comportamento tixotrópico.

Neste sentido, o segundo dos obxectivos xerais é determinar o efecto da incorporación de árido groso reciclado de formigón nas propiedades no estado fresco do formigón autocompactante. O estudo céntrase no seu comportamento reolóxico (incluíndo as tres características de traballabilidade e a evolución temporal tanto destas como da súa reoloxía), na súa robustez e na análise da súa tixotropía (avaliando, ademais, a súa influencia na adherencia entre capas).

Para a consecución destes obxectivos desenvólvese unha extensa campaña experimental que se divide en tres fases. Na primeira delas, chamada "Reoloxía", estúdanse catro tipos de formigón autocompactante, un formigón de referencia e tres formigóns reciclados. As porcentaxes de substitución de árido groso natural por árido groso reciclado de formigón son 0%, 20%, 50% e 100% (en volume). Nesta primeira fase utilízanse, para cada mestura, tres métodos de amasado:

1. Método M1: os áridos utilízanse en condicións secas e engádese unha cantidade de auga extra durante o amasado. Esta calcúlase para compensar a absorción do árido reciclado aos 10 min (80% da absorción ás 24 h).
2. Método M2: o árido reciclado presatúrase ata o 80% da súa capacidade de absorción de auga total inmediatamente antes do amasado.

3. Método M3: o árido reciclado utilízase cun 3% de humidade natural e de novo engádese unha cantidade de auga extra durante o amasado conforme ao mesmo criterio que no método M1.

Na segunda fase, denominada "Robustez", realízase unha campaña experimental para avaliar a robustez do formigón autocompactante contendo árido reciclado. Estúdanse dúas series de mesturas de formigón autocompactante con diferentes porcentaxes de árido groso reciclado de formigón (0%, 20%, 50% e 100%), unha serie co árido en condicións secas (método M1) e a outra incorporándoo na amasadora cun 3% de humidade (método M3). Nesta segunda fase, analízase a capacidade do FACR para manter a súa traballabilidade e as súas propiedades reolóxicas ao longo do tempo cando se introducen variacións na auga (± 3%), no superplastificante (± 5%) e no cemento (± 3%) de forma independente.

En ambas as fases de traballo, "Reoloxía" e "Robustez", mídense as propiedades no estado fresco do FACR mediante reómetro (tensión de fluxo limiar e viscosidade plástica) e mediante ensaios empíricos (espallamento, caixa en L, funil en V, anel xaponés e segregación por peneira). Tanto os ensaios empíricos como os reolóxicos realízanse sobre todas as mesturas a 15, 45 e 90 min desde o contacto entre cemento e auga.

Para analizar o comportamento no estado endurecido do FACR, en ambas as fases, determinouse para cada mestura a densidade no estado fresco e endurecido e a resistencia a compresión a 3, 7 e 28 días.

A terceira fase, chamada "Tixotropía", céntrase na análise do comportamento tixotrópico do FACR. Ademais, avalíanse a adherencia e a permeabilidade á auga que poden desenvolverse entre tongadas sucesivas de formigón autocompactante reciclado tras un certo período de repouso. Para este propósito, estúdanse catro mesturas de FACR con 0%, 20%, 50% e 100% de árido groso reciclado. Este árido utilízase seco e engádese unha cantidade extra de auga durante o amasado para compensar a súa absorción aos 10 min (método M1).

Nesta terceira fase, en relación co comportamento no estado endurecido, mídense a resistencia a compresión, a resistencia a tracción e o módulo de elasticidade a 28 días para cada mestura.

En relación co comportamento en estado endurecido, creouse unha base de datos con resultados publicados sobre formigón vibrado reciclado e axustáronse diferentes coeficientes de corrección para adaptar as expresións normativas a este tipo de formigón. Así mesmo, axustáronse expresións preditivas específicas para o formigón vibrado reciclado como alternativa ás formulacións das normativas. Finalmente, confirmouse que, tanto os coeficientes de corrección como as expresións específicas, poden utilizarse no FACR coa mesma precisión que no formigón vibrado reciclado. Polo tanto, a incorporación de árido groso reciclado de formigón afecta a resistencia a compresión, o módulo de elasticidade e a resistencia a tracción do formigón autocompactante na mesma medida na que se afectan no formigón vibrado.

En relación co comportamento no estado fresco, pódese concluír que as mesmas relacións entre parámetros empíricos e entre parámetros empíricos e propiedades reolóxicas se poden utilizar para formigóns autocompactantes convencionais e reciclados. Ademais, conforme aos resultados obtidos e en consonancia con outros autores, ningún dos ensaios empíricos se encontra adecuado para definir todas as características clave da traballabilidade do FACR como un único ensaio, e non hai ningunha combinación de ensaios que lograra unha validez universal.

A análise do comportamento reolóxico mostra que a particularidade do FACR radica na cantidade de auga extra necesaria para compensar a absorción do árido groso reciclado durante o protocolo de amasado, que inflúe na relación auga/cemento efectiva ($(a/c)_{ef}$), e nas características intrínsecas do mesmo (forma, textura e contido de finos). Neste traballo, dado que o árido reciclado e o natural presentan formas similares (ambos os dous son de machaqueo), son principalmente a textura rugosa e o contido de finos no árido reciclado e xerados durante o amasado polo desgaste do morteiro adherido, os que modifican o comportamento reolóxico do FACR. Todas estas singularidades levan a diferentes relacións ou curvas "variacións reolóxicas – $(a/c)_{ef}$" e "variacións reolóxicas – $\varnothing/\varnothing_{max}$" nun FACR comparado cun formigón autocompactante convencional.

As diferencias obtidas entre o comportamento dun formigón autocompactante convencional e o dun FACR co transcurso do tempo dependen da cantidade de auga compensada no protocolo de amasado. Esta determina a rexión das curvas "variacións reolóxicas – $(a/c)_{ef}$" onde o formigón se deseñou. Está claro que a relación auga/cemento efectiva do FACR evoluciona co tempo de acordo á evolución da absorción do árido groso reciclado. Entón, é máis probable que a rexión con pendente pronunciada das curvas mencionadas se alcance cando se utilicen altas porcentaxes de árido reciclado, cando se deseñe o FACR cunha relación auga/cemento baixa e/ou cando se mida o comportamento a longo prazo do FACR. Nestes casos, é de esperar un comportamento reolóxico dependente do tempo nun FACR diferente dun FAC, do contrario o comportamento reolóxico ao longo do tempo do FACR será similar ó dun FAC.

A análise da robustez do FACR realízase a través do cálculo de parámetros de sensibilidade para definir os factores que afectan esta propiedade en maior medida. Tamén se efectúa unha aproximación estatística para determinar que ensaios proporcionan maior sensibilidade cando se avalía a robustez do FACR.

Ambas as análises mostran que o principal parámetro que afecta a robustez do FACR é a auga. Por outro lado, dado que o control da auga resulta máis difícil neste formigón, debido á maior absorción do árido reciclado, este debe ser máis exhaustivo que no FAC convencional. Ademais, a aproximación estatística, baseada no coeficiente de concordancia de Kendall e no coeficiente de correlación de Spearman, utilizouse satisfactoriamente para identificar as propiedades clave a medir para avaliar a robustez do FACR: tensión de fluxo limiar estática (15 min), viscosidade plástica (15 min), tempo e diámetro do ensaio de espallamento (15 min), diámetro do ensaio co anel xaponés (15 min) e a resistencia á segregación por peneira.

Finalmente, observouse que o FACR é menos robusto que o formigón autocompactante convencional. Isto débese a que o FACR presenta as curvas "parámetro reolóxico – $(a/c)_{ef}$" e "parámetro reolóxico – $\varnothing/\varnothing_{max}$" con maior pendente que as do formigón autocompactante convencional. Desta forma, cando se utilizan altas porcentaxes de árido groso reciclado existe unha maior probabilidade de alcanzar a rexión de pendente pronunciada destas curvas de maior pendente. Isto causa cambios significativos na tensión de fluxo limiar estática e, de forma similar, cambios substanciais na viscosidade plástica e nos parámetros empíricos. Adicionalmente, a fabricación dos formigóns con áridos con contido de humidade dificulta máis o deseño de FACRs robustos, como tamén ocorre nos formigóns autocompactantes convencionais.

Polo tanto, en conclusión, a robustez do FACR dependerá da cantidade de auga compensada no protocolo de amasado e na rexión da curva "parámetro reolóxico – $(a/c)_{ef}$" onde o formigón se deseñou (preto ou lonxe da zona de pendente pronunciada).

O estudo do grao de tixotropía do FACR abórdase utilizando varios métodos de ensaio e protocolos: curvas de ruptura estrutural a diferentes velocidades de rotación, curvas de fluxo de histérese e tensión de fluxo en repouso (tamén chamada tensión de fluxo estática). Adicionalmente, avalíase a influencia da tixotropía ou o efecto da reestruturación en repouso no comportamento mecánico do FACR a través da medida da adherencia entre capas utilizando ensaios a flexión e ensaios de permeabilidade á auga. Os tempos entre dúas tongadas sucesivas de FACR son de 0, 15, 30 e 60 min.

De acordo aos resultados obtidos, pódese concluír que os tres métodos utilizados proporcionan, aínda que medindo diferentes índices, resultados similares sobre o grao de tixotropía de cada mestura, isto quere dicir que cos tres métodos se obteñen as mesmas conclusións cualitativas.

Adicionalmente, obsérvase que os ensaios de curvas de ruptura estrutural e de tensión de fluxo en repouso proporcionan maior sensibilidade na aproximación ao comportamento tixotrópico.

Como a tixotropía depende da composición da pasta e esta é similar en todos os formigóns, as diferencias observadas nos índices de tixotropía das diferentes mesturas son pequenas, constatándose un lixeiro incremento cando a porcentaxe de substitución é total. Este incremento débese á diferencia na relación auga/cemento efectiva, resultado da absorción non compensada, e á maior cantidade de finos xerados polo vello morteiro adherido ao árido groso reciclado.

A relación auga/cemento efectiva deseñada nesta fase sitúa aos formigóns na rexión de pendente suave das súas curvas “variacións reolóxicas – $(a/c)_{ef}$”. Desta forma, a súa evolución temporal ata o tempo considerado nesta fase de traballo (debida á absorción non compensada), non implica cambios significativos na composición das pastas dos FACRs. Polo tanto, a velocidade de reestruturación é similar en todas as mesturas estudadas.

Os resultados de resistencia a flexión residual e variación da profundidade de penetración de auga indican, para todos os tempos entre capas considerados, que os FACRs desenvolven unha adherencia entre capas similar á do formigón autocompactante de referencia. Soamente para un tempo entre capas de 60 min, observouse que, para a porcentaxe de substitución total, a diminución na adherencia é lixeiramente máis notable. Isto débese a que a tixotropía dos FACRs estudados é lixeiramente maior cando se utilizan altas porcentaxes de substitución.

Finalmente, en consonancia coas conclusións da análise da reoloxía, cando se utilizan altas porcentaxes de substitución, cando o FACR se deseña cunha relación auga/cemento baixa (na rexión de pendente pronunciada das curvas “variacións reolóxicas – $(a/c)_{ef}$” e/ou cando se mide o comportamento autocompactante a longo prazo, a velocidade de reestruturación e a adherencia entre capas poden verse máis afectadas nos FACRs que no formigón autocompactante convencional.